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SPILL RISK ANALYSIS PROGRAM:
METHODOLOGY DEVELOPMENT AND DEMONSTRATION
FINAL REPORT

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

APRIL 1977

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16. Abstract
This report describes research and results in the development and demonstration of systematic methods of assessing the effectiveness of either proposed or recently implemented merchant marine safety regulations. The methods have been designed primarily to assist Coast Guard regulatory decision-makers in their selection of alternative means of reducing marine transportation casualties and spills of hazardous or polluting materials. The methodology involves both analytical and logical modeling of merchant marine operations and the casualty process. Analytic modeling of ship collisions is primarily in terms of the physical parameters (e.g., vessel size, speed, maneuverability) of the system, but human response parameters are also considered. Logical modeling of casualties addresses the effects of changes in regulations and involves the structured conduct of quasi-experiments using the Coast Guard data base of marine casualty reports. A preliminary analysis of the Coast Guard Pollution Incident Reporting System (PIRS) is also included. This report supplements, but does not replace information contained in Report No. CG-D-15-75, Spill Risk Analysis Program Phase II Methodology Development and Demonstration (NTIS AD-785026).

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DOT USCG SPILL RISK METHODOLOGY DEVELOPMENT APRIL 1977

METRIC CONVERSION FACTORS

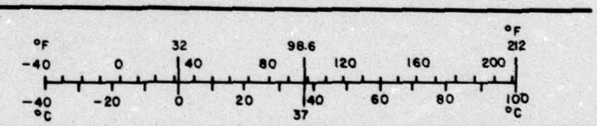
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



(2)

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This work was performed at Operations Research, Inc. within, initially, the Resource Analysis Division and completed within the Transportation Systems Division. The research was carried on under the general technical direction of Leonard A. Stoehr, Program Director. The principal investigators in the various parts of the project were as follows:

- Quasi-Experimental Method: Mr. C.H. Morgan, Dr. F.J. Reifler, Mr. L.A. Stoehr, Mr. P.M. Tullier
- Scenario Model: Mr. C.H. Morgan, Dr. F.J. Reifler, Mr. P.M. Tullier
- Analysis of Pollution Incident Reporting System (PIRS) data: Mr. W.D. White.

The following members of the ORI staff contributed significantly to various phases of the study: Dr. S.G. Kneale, Messrs. R.B. Dayton and H. Richardson, Ms. D. Cauthorne and Mrs. F. Gianaras.

This work was performed under the close technical supervision of Dr. John S. Gardenier of the Office of Research and Development, U.S. Coast Guard. Primary monitors were Cdr. Richard A. Sutherland and Mr. Paul V. Ponce at the Office of Merchant Marine Safety.

The Coast Guard has established a Risk Analysis Advisory Board to review and comment on all risk analysis research projects. The Board is composed of representatives from interested divisions and staff of the Chief of Staff, the Office of Merchant Marine Safety, the Office of Marine Environment and Systems, and the Office of Research and Development. A liaison member from the National Transportation Safety Board is also included. We have found the comments and criticisms of board members on the review of interim reports on this project to be invaluable.

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EXECUTIVE SUMMARY

INTRODUCTION

This report presents the results of a major research project directed toward the development and demonstration of scientific methods for measuring the effectiveness of merchant marine safety programs. It represents the first sustained effort in a program aimed at developing a formal system for the evaluation of costs and benefits related to specific actions proposed under the United States Coast Guard merchant marine safety function. This research was performed under the Department of Transportation, United States Coast Guard contract DOT-CG-31571-A. The report has three levels of reporting detail. This executive summary presents a non-technical overview of the methods developed and the key findings as they relate to Coast Guard regulatory decisions. The main body of the report treats three specific projects undertaken. Volume I presents the development and demonstration of two methods for approaching decision-making problems: (1) the Quasi-Experimental Method for analysis of casualty records to assess the potential effectiveness of safety measures and to clarify the sources of collision causes; and (2) the Scenario Model for exploring ship collision risk and avoidance capabilities. Volume II examines a new area of research, that of shore-based facilities, from the standpoint of applicability of the Volume I methods which were aimed primarily at ship collision problems. In other words, Volume II is primarily an effort in problem definition. Supporting data and more technical details of the research are provided in appendices at the end of each volume of the report.

This report supplements and extends, but does not replace, Coast Guard Report No. CG-D-15-75, Spill Risk Analysis Program Phase II Methodology Development and Demonstration. This earlier report is now available through the National Technical Information Service under AD-785026.

MAJOR ACCOMPLISHMENTS

The major accomplishments of this phase of the project have been:

- Development of a logical, repeatable and largely quantitative experimental design for the evaluation of narrative data. This method, while demonstrated here in its application to vessel collision reports, has application to a wide range of Coast Guard problems where information is available in primarily narrative form.

- Development of a scenario model which can dynamically examine the vessel collision process in a simplified representation of physical parameters of the vessel-waterway system.

- Analysis of Pollution Incident Reporting System (PIRS) data for risk implications relative to both vessel and shore facility spills.

THE RESEARCH PROBLEM

The application of operations research methods to problems of safety regulation is fairly new. Established techniques, most of which have been developed for military and business problems, are not generally suitable in the safety field. Several general principles from the other areas do apply however. One is the concept of a measure of effectiveness (MOE). The MOE is a quantitative concept by which system changes can be evaluated. It is a "yardstick" which measures in an objective manner real-world problems that are usually addressed as matters of subjective judgment. In safety regulation, a desirable MOE would be the improvements or increases in safety that might be realized through various regulatory initiatives. Such a direct measure has not yet been formulated. However, if we can measure decreasing risk, we are measuring an equivalent increase in safety. Therefore, the concept which has been adopted in this research is that of a basic equation of risk management:

$$R_1 + \Delta R = R_2 \tag{S1}$$

where:

R_1 = level of risk assessed prior to a system change

ΔR = change in risk associated with the change under examination

R_2 = level of observed, or expected risk after the change.

All research to date has been oriented toward methods for measuring the change in risk associated with specific Coast Guard actions.

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METHODS DEVELOPMENT AND DEMONSTRATIONS

The research which is the subject of this report can be subdivided into three general areas. Two of these, the quasi-experimental method and the scenario model, are addressed in Volume I. Volume II presents the results of the Pollution Incident Reporting System (PIRS) data. Each of these projects will now be presented in more detail.

Quasi-Experimental Methods (QEM)

Development. The quasi-experimental method (QEM) is basically an objective, scientific means for deriving quantitative information from narrative material. It is an experimental design which was developed for evaluating information available from Coast Guard casualty reports, but it should be equally applicable to any problem where narrative materials comprise a significant portion of the available data.

Faced with a set of problems whose solution could possibly be found in Coast Guard narrative casualty reports, project researchers designed a general experimental format which will produce valid, repeatable, quantified information from this data. The QEM, which was the product of this effort, consists of developing a logical model of a normal, collision-free encounter between two ships. Collision-event sequence diagrams and safety analysis logic trees (SALT) are then produced from a review of a small sample of casualty reports. A small evaluation project was undertaken to examine the utility of the SALT in structuring vessel casualty investigation and reporting systems. It was concluded that, due to the lack of an intrinsic sequencing structure, the SALT was useful primarily as a system for expost facto statistical analyses of casualties. A more detailed report of this project is contained in Appendix G of this volume.

Using the SALT and the specific problem to be addressed, a Casualty Analysis Gauge is developed. The Casualty Analysis Gauge is a rigidly structured set of questions which must be answered relative to each casualty report reviewed by each of two independent readers. After an independent review is completed, the two readers confer in an effort to resolve any differences in their answers. The number of differences tends to measure the accuracy and objectivity of the logic within the gauge. Four Casualty Analysis Gauges were developed. Two were used for analysis of the effectiveness of bridge-to-bridge radiotelephone regulatory action. The third addressed collision avoidance radar regulatory action, and the fourth addressed collision causes. In general, the agreement rate for each of the four gauges tested was greater than 95 percent. The results presented in the following discussion of the QEM demonstration are based on the reading of a total of approximately 700 collision reports. Two sample populations were used. The bridge-to-bridge radiotelephone experiment used a 30 percent random sample of collision reports concerning vessels subject to these regulations during the period FY 1964-1974. The collision avoidance radar system experiment used a sample composed of all ship collision reports involving at least one vessel of 10,000 gross tons or more during the period FY 1970-1974. The collision cause Casualty Analysis Gauge was applied to both of these populations. Each report was read by at least two reviewers.

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A second general concept of operations research which has been applied in this project is that of an initial analysis of the overall problem. To quote Webster, the definition of analysis is the separation of a whole into its component parts. In other words, like a convict on a rock pile, the operations researcher tries to make little ones out of big ones. In relation to the project reported herein, an initial effort was directed toward identifying the more important sources and causes of spills. Ship collisions were selected as an area for more detailed analysis. The quasi-experimental method and the scenario model are two tools developed for examination of the ship collision process.

RISK ANALYSIS RESEARCH PROGRAM: BACKGROUND

The risk analysis research program was initiated in the spring of 1971. It currently involves research in four separate areas:

- Spill-risk analysis—assessment of risk that a vessel or facility spill will occur; evaluation of regulatory effectiveness on national and local scales
- Vulnerability analysis—assessment of threats to people, property, and the environment due to spills emanating from vessels or shore facilities
- System cost analysis—assessment of economic impacts on government, industry, and individuals as a result of implementing alternative regulatory actions in spill prevention
- Integration of risk-reduction (safety) benefits and economic impacts to assess, on a cooperative basis, various spill prevention actions.

Figure S.1 shows a schematic diagram of this systems approach to risk management.

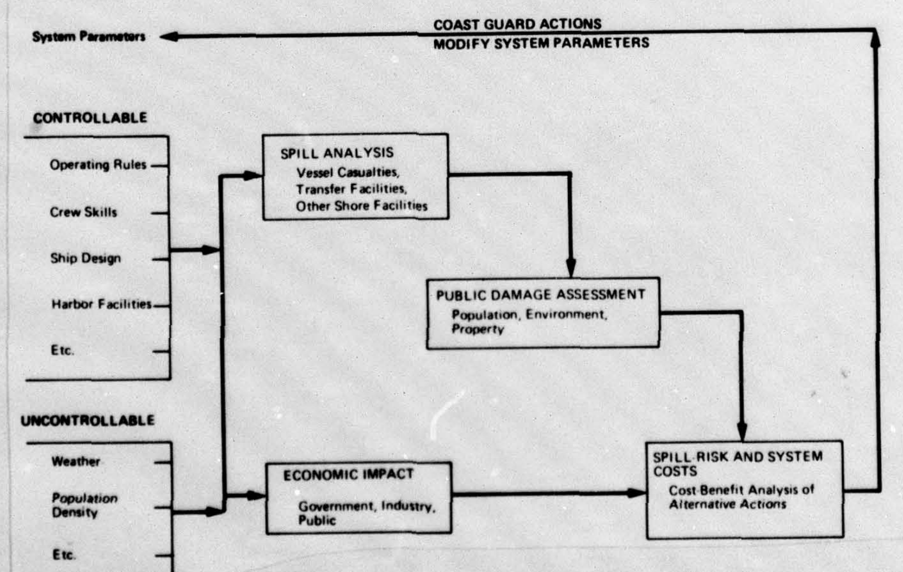

FIGURE S.1. RISK MANAGEMENT - THE SYSTEMS APPROACH

(8)

Demonstration. The three analyses which were conducted using the QEM are:

- **Bridge-to-Bridge Radiotelephone Effectiveness**
  This analysis assesses the effectiveness of a newly implemented regulation through a time-based comparison of communication problems in vessel collisions.

- **Collision-Avoidance Radar System Effectiveness**
  This analysis predicts the theoretical maximum effectiveness of a proposed new regulation and identifies factors limiting its potential effectiveness.

- **Collision Causes**
  This is a problem definition study.

The principal findings of each of the three analyses are:

Bridge-to-Bridge Radiotelephone Effectiveness

- The percentage of collisions potentially preventable by the use of bridge-to-bridge radiotelephone since 1970 is less than one-half as large as the same percentage was during the six years prior to 1970 (see Figure S.2). This provides an estimate that an average of about 25% fewer collisions per year are preventable through use of bridge-to-bridge radiotelephone. It appears that this effectiveness would be greater were it not partially offset by increases in collisions involving communication problems despite use of the bridge-to-bridge radiotelephone.

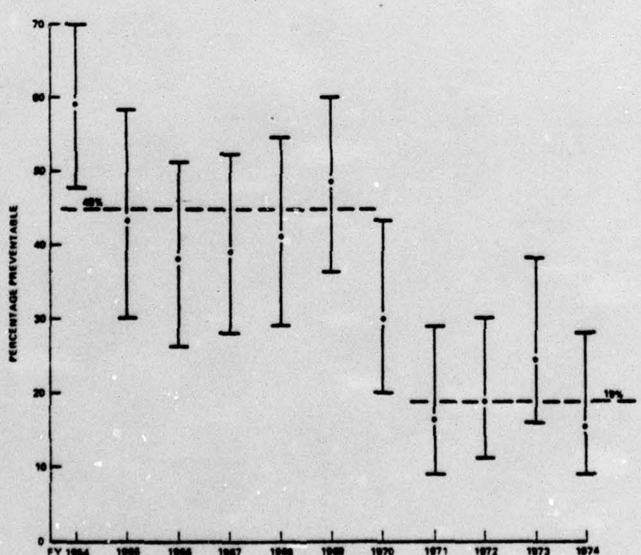

FIGURE S.2. PERCENT OF COLLISIONS POTENTIALLY PREVENTABLE BY BRIDGE-TO-BRIDGE RADIOTELEPHONE (95 PERCENT CONFIDENCE LIMITS)

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- With 99 percent assurance, it can be said that during FY 1964-1969, the proportion of collisions potentially preventable by the use of bridge-to-bridge radiotelephone was greater than 38 percent; in FY 1971-1974, this percentage was less than 27 percent. (See Figure S.3.)

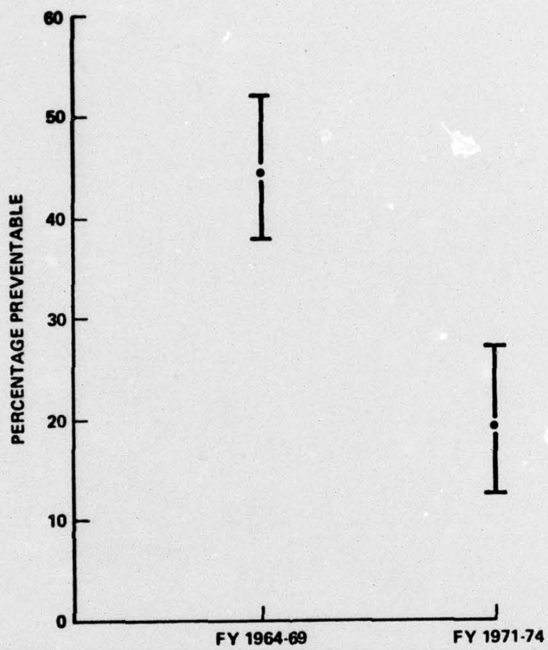

FIGURE S.3. CUMULATIVE PERCENT OF COLLISIONS POTENTIALLY PREVENTABLE BY USE OF BRIDGE-TO-BRIDGE RADIOTELEPHONE (99 PERCENT CONFIDENCE LIMITS)

- The number of collisions reported has remained relatively constant over the period FY 1968-1974, and has ceased an increasing trend observed in earlier years.

- All applicable collision exposure statistics tend to indicate that the number of reported collisions should be rising, unless effective safety improvements are operative.

- <u>Conclusion</u>. The increased capacity for collision avoidance generated through the use of bridge-to-bridge radiotelephone has resulted in an effective decrease in the number of ship collisions by holding this number constant in the face of a large number of upward pressures. Problems in utilization limit the potential maximum effectiveness.

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Collision Avoidance Radar System Effectiveness

- Assuming a 100 percent reliable collision avoidance radar system, a theoretical maximum of about 10 percent of the collision cases reported during the period FY 1970-1974 involving at least one ship of greater than 10,000 gross tons can be judged potentially preventable by the installation of the system.

- In only 32 percent of the cases was detection and evaluation of the collision threat a problem for the large ship involved.

- In 22 percent of the cases in which detection and evaluation were problems, collision avoidance radar systems were ineffective in solving the problem.

- Conclusion. Installation of collision avoidance radar systems would not prevent many reported collisions involving ships displacing greater than 10,000 gross tons.

Collision Causes

- The collision cause experiment was aimed at definition of the ship collision problem as it applies to possible future Coast Guard actions. From this point of view, project personnel developed a Casualty Analysis Gauge that tended to classify collision causes into increasingly precise categories. The casualty report samples used in each of the other experiments were both used to evaluate the possible differences between the two sample populations.

- In the comparative evaluation of the 30 percent random sample (which was dominated by inland waterway collisions) and the sample of all collision reports involving one vessel of greater than 10,000 gross tons (where a significantly greater percentage of collisions occurred in coastal areas and on the high seas), considerable correspondence was found in the percentages of collisions attributable to the various cause categories used. There were only three major categories of collision causes showing significant differences as follows:

Collision Cause Category	30 Percent Sample	10,000 Ton Sample
Vessel and Waterway Design	50%	30%
Environment	33%	46%
Human Factors	82%	89%

(11)

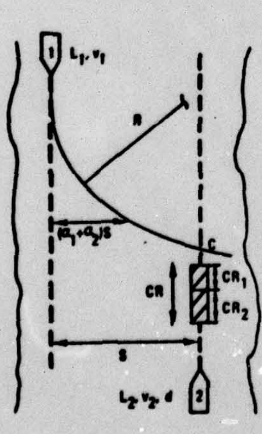
The reasons for differences in the vessel and waterway design and environment become apparent on close examination of the data within the report. The reasons behind the difference in the human factors result are not obvious.

- The large percentage of human factors-related collision causes (82 percent in the 30 percent random sample; 89 percent in the greater than 10,000 ton sample) confirms the importance of the human element in the collision equation, as has been reported in other studies on this subject. While the importance of human factors is confirmed, there is a very real problem in making sense out of a large variety of human errors when no single error or small group appears to predominate.

- Conclusion. If the Coast Guard wishes to significantly reduce the numbers of marine collisions, the potentially most profitable area in which to operate is that of human factors. A serious problem exists in the fact that, in the marine human factors field, very little has been achieved in the definition of measures of effectiveness and the structuring of the overall area in the sense previously discussed under the Research Problem heading.

Scenario Model

Development. The scenario model is a dynamic computer simulation of the two-ship collision situation. The methodology of the model is based on the concept of a "collision region." A ship is said to be in a collision region if it is in a potential collision situation and does not have sufficient independent maneuvering capability to avoid collision. The size of the collision region depends upon a number of parameters, including the physical dimensions of the two ships, their relative speed and heading, and their ability to respond to the situation in terms of their maneuvering characteristics, and the time delays (human factor and mechanical) required to initiate avoiding actions. The collision region for the most common collision scenario is depicted in Figure S.4.



CR = Collision Region

CR_1 = "Struck" Subregion

CR_2 = "Striking" Subregion

C = Collision Point

Other alphanumeric quantities indicate model input parameters used in the computation of CR

FIGURE S.4. COLLISION REGION CONCEPT

The scenario model development was originally reported in Coast Guard Report CG-D-15-75 (see Introduction). During the interim year, the original model has been extensively extended and improved. The model now addresses the following scenarios: meeting, overtaking, long-range crossing, and sudden appearance. Bend situations are not addressed. Collision avoidance maneuvers include accelerating, decelerating, and turning. Combinations of course and speed changes are also included. Modifications to the original model are shown below:

Original Model	Present Model
• Small angle approximations used in computing ships' positions.	• Exact calculations.
• Ships follow circular track when turning.	• More accurate spiral track defined.
• Ships maintain constant speed when turning.	• "Drag" deceleration effects considered.
• Ships are mathematically treated as a point.	• Ships have length, beam, and pivot point specified. Angle of attack (crabbing angle) is considered in turns.
• Combined perception and mechanical delay response parameter (ALPHA)	• Separation of response time lags – Human perception (Alpha$_1$) – Ship System (Alpha$_2$)

A FORTRAN program has been developed for use by Coast Guard personnel. The model results are expressed in terms of sensitivity analyses, showing the expected gains and losses to be realized when a given base line case is modified by changing one or more parameters.

Demonstration. The sensitivity analyses produced by the Scenario Model have two principal areas of application. The first is to problems of vessel traffic service where assistance may be needed, in specific areas, by Captains of the Port (COTP) and, in a more general sense, by officers dealing with regulatory problems at the headquarters level. The second addresses problems of vessel controllability and would be primarily useful at the headquarters.

Vessel Traffic. To illustrate the way in which the scenario model might be applied to a vessel traffic problem, we will outline a hypothetical situation and then explain the use of the model and the results which might be anticipated.

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Example. The Hudson River main ship channel between Manhattan Island and New Jersey is approximately one mile (6,000 feet) in width. It is proposed that this channel be divided into two channels, one for northbound traffic and one for south. These two channels are to be separated by a mediam strip 1,000 feet wide. This separation is to be achieved by the placement of two lines of buoys marking the boundaries of the median strip. Let us assume that current traffic in the river, on the average, tends to follow a track near the middle of the east and west sides of the channel (i.e., 1,500 feet from both the east and west lines of channel buoys) and that, after the addition of the two lines of new buoys, traffic will tend to stay toward the center of both the north and southbound channels. If these assumptions are correct, we have then increased the average traffic separation in the river from 3,000 feet to 3,500 feet. How much is the change likely to reduce the probability of collisions in this portion of New York Harbor?

By estimating the range of maneuverability of the types of ships that we are most concerned about (i.e., large and small limits on advance, transfer and turning radii), we can use the scenario model to place upper and lower bounds on the decrease in probability of collision. As sensible seamen, we know that this is not a complete answer. The separation area would also tend to assist bridge personnel in the early perception of a potential collision situation (i.e., when an oncoming ship enters the median strip). This effect can also be tested using the scenario model. We have not considered the problem of cross-channel traffic, the probable effects restricting maneuvering room in overtaking situations (which also can be tested) and a large number of other factors. We have not completely solved the problem posed by the question, but we have increased our knowledge in relation to one part of the problem and thereby reduced the complexity of the overall situation.

Vessel Controllability. To illustrate the use of the scenario model in dealing with a vessel controllability problem, Figure S.5, which shows some of the base case sensitivity results, will be used.

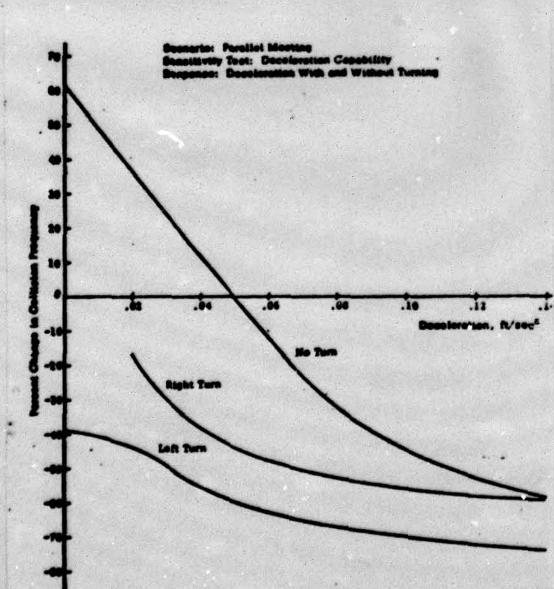

FIGURE S.5. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

Let us assume that, in the design review of a new LNG carrier, the Coast Guard wishes to examine the change in collision-avoidance potential of changing the ship's deceleration capability. If Figure S.5 accurately represents the characteristics of the design, we can see that the current deceleration capability is .05 ft/sec^2. No consideration is given to how a change might be achieved. Possible means could be changing propellor pitch and number of blades, increasing shaft horsepower for backing, or installation of a scoop-brake system. Whatever the design change used, we can see that if we can increase deceleration capability to .08 ft/sec^2 we can reduce collision probability by between 30 and 40 percent without any accompanying course changes. If we are willing to accept the danger of running aground by leaving the channel in a turn to starboard, we can increase this reduction to 50 percent. If we can be assured that the other ship is out of control and has no chance of correcting the turn that is taking it across the track of the LNG ship, we could turn to port and further reduce collision potential to between 60 and 70 percent. In the example shown in Figure S.5 we have not considered any changes in turning characteristics or other parameters as a result of the changed deceleration capacity. In an actual study of this problem such effects would need to be considered. This could be done either using the model or by computations outside the model. The important point is that, while the predictions from a model such as this one will necessarily be gross, the general effect can be assessed and, as in the case of the vessel traffic control example, the range of uncertainty reduced.

POLLUTION INCIDENT REPORTING SYSTEM DATA ANALYSIS

Approach

The purpose of this portion of the project was to review the general facilities problem and determine whether the operations research techniques developed for vessel spill-risk analysis might have application. The primary source of information for this study was the Pollution Incident Reporting System (PIRS) data base which is maintained at U. S. Coast Guard headquarters under the supervision of the Office of Marine Environment and Systems (G-WEP-1). The information derived from the PIRS was supplemented by interviews with headquarters personnel and visits to the Captain of the Port offices at Baltimore and San Juan, P.R.

From the very start of this project, the importance of the PIRS data base was apparent. The PIRS is not simply the only centralized source of spill statistics available; moreover, it determines, to a very great extent, the level of detail required in reports from field activities. The PIRS is relatively new, having been established in 1970. The PIRS was extensively modified in 1973 to provide more detailed information on certain particulars. For the analysis reported here, which focuses on data for 1971, 1972, and 1973, it was necessary to revise some of the PIRS source and cause categories in order to provide continuity over the full three-year period.

Findings

The following are the principle findings of this initial examination of the spill risk problem as it relates to shore-based facilities rather than vessel casualties:

- The nature of the spills originating from vessels and coming from transportation-related facilities is basically different. In the vessel spill context, the challenge is to reduce a small number of comparatively infrequent occurrences which, on the average, result in a large volume of pollutant discharge. Within transportation-related facilities, the solution to reducing spill volume requires achieving large reductions in the number of incidents. The incidents are numerous, almost routine, and generally result from various kinds of structural and equipment failures.

- Coast Guard reporting systems for vessel casualties and pollution incidents, which often contain information of a similar nature, are not coordinated. The information contained in vessel casualty and pollution incident reports and their associated data banks overlaps to a certain degree, yet it is difficult to correlate incidents which appear in both data systems. It is understood that efforts toward coordination are underway.

  The lack of availability of narrative pollution incident reports at Coast Guard headquarters limits the degree of analysis of this information. Narrative pollution incident reports are on file at Coast Guard commands in the field. Similar reports of vessel casualty incidents are available within Coast Guard headquarters and have proven very useful in past analyses in the Spill Risk project.

- Approximately two-thirds of the total volume of pollution originates from three kinds of incidents:

Incident Type	Volume Reported
—Vessel casualties	~30%
—Natural phenomena affecting non-transportation-related facilities	~23%
—Material, structural, or equipment failures at transportation-related facilities	~13%

  Within the portion of these incidents most amenable to Coast Guard influence, i.e., that portion whose causes are preventable (excluding natural phenomena, for the short term) and whose sources are within Coast Guard

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direct regulatory jurisdiction, the greatest contribution to pollution volume comes from collisions, rammings, and groundings of tank ships and tank barges. These percentages consider only legislation assigning the Coast Guard direct responsibility for marine safety. They do not consider the Coast Guard's residual jurisdiction for prevention of pollution from non-marine, transportation-related sources established under Section 311(j) of the Federal Waterway Pollution Control Act (FWPCA). The dominance of tank ship/tank barge casualties recorded in the 1971-1973 statistics is not likely to fade in the near future and may well increase. The second greatest contribution comes from material, structural, and equipment failures at on-shore transportation-related facilities.

- A majority of Coast Guard pollution reporting effort at field activities is devoted to investigation and reporting of small spills which contribute little to the total volume of pollutant materials released. Approximately one-half of all incidents reported involved a discharge of less than 20 gallons. Nearly 95 percent of incidents reported involved spills of less than 1,000 gallons. Discharges of less than 1,000 gallons accounted for only 2 percent of the total volume of pollutants reported. According to a small number of interviews with personnel experienced in pollution investigations, the administrative time and effort required for investigation and reporting of spill incidents is effectively independent of the volume of the spill, unless an extraordinarily large, catastrophic occurrence takes place. It is recognized that the ecological effects of an accumulation of frequent small spills may be significant and that this factor must be considered in any policy review.

Conclusions

- The Coast Guard may wish to reevaluate its policy regarding the investigation and reporting of spill incidents. As previously noted, much of the pollution reporting effort at field activities is related to very small volume incidents and to incidents where the source is beyond Coast Guard regulatory jurisdiction. It is recognized that ensuring cleanup of discharges into waterways is a Coast Guard responsibility, and therefore determination of source is valuable if punitive action is needed. Nevertheless, the inability of the Coast Guard to directly influence the conditions under which future spills might be prevented seems to be a significant weakness in Coast Guard regulatory powers.

Possible means of relieving the workload in the field might be:

a. Allowing more discretion by field activities in setting investigation requirements.

b. Examine the value of combining vessel casualty reports and PIRS reports for those vessel casualties resulting in significant spills.

- Spill-risk analysis operations research techniques can be of significant value in the evaluation of the facilities spill problem. The QEM technique can be applied without modification to either narrative pollution incident investigation reports or the on-scene coordinator reports in the case of major spills. The information contained in these reports is very similar to that in marine casualty investigation reports. The QEM would be useful in testing either the effectiveness of regulations recently placed in effect or the potential utility of proposed regulatory initiatives.

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OVERVIEW OF CONTENTS

(This listing indicates the major sections of the report, which is divided into two volumes and four parts. The first three parts are contained in this volume. The fourth part is contained in Volume II. Each part is preceded by detailed tables of contents. Figures and tables are also listed by part. Appendices are included at the end of each volume.)

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PART 1:

INTRODUCTION

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PART 1: INTRODUCTION

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INTRODUCTION

This report describes research and results in the development and demonstration of scientific methods applicable to the systematic management of marine transportation risks. It is the concluding report of a segment of a research and development effort in support of the U.S. Coast Guard Commercial Vessel Safety program. This research was performed under the Department of Transportation, United States Coast Guard contract DOT-CG-31571-A, by Operations Research, Inc. This report updates and expands material previously published in Spill Risk Analysis Program, Phase II: Methodology Development and Demonstration of August 1974. That report is available from the National Technical Information Service, Springfield, Virginia, as accession number AD-785-026. This report has been organized to stand alone so that only those readers interested in the development process and in a recommended program of human factors research need reference the earlier report.

THE OPERATIONAL PROBLEM

The United States Coast Guard is the Federal agency charged with responsibility for safety regulation of commercial vessel operations on the navigable waters of the United States, and of U.S. commercial vessels in their operations world wide.

Federal regulation of the merchant marine began in 1838, prompted by a number of explosions of steamboat boilers causing numerous passenger deaths. By 1852, a Steamboat Inspection Service was formed with authority for safety inspection of steamboats, licensing of pilots and engineers, and regulation of vessel operations through nautical rules of the road. After a series of reorganizations and expansions of authority, the functions of maritime safety regulation, and other missions, were formally consolidated in the Coast Guard under the Reorganization Act of 1946.

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Currently, the Coast Guard's scope of regulatory authority and operations with respect to maritime safety includes:[1]

- Licensing and documentation of merchant marine officers and seamen
- Standards and exceptions for vessel designs and equipment
- Periodic inspection of vessels
- Maritime accident investigation and recordkeeping
- Requirements for shipboard stowage and containment of hazardous materials
- Requirements for handling dangerous cargoes within or contiguous to waterfront facilities
- Security of vessels and waterfront facilities
- Promulgation of nautical rules of the road
- Installation and maintenance of aids to navigation including buoys, lights, and electronic navigation systems
- Anchorage regulation
- Location and design of bridges over navigable waters and drawbridge operations
- Control of oil and hazardous substances pollution
- Movement of hazardous cargoes in ports.

In addition, the Ports and Waterways Safety Act of 1972 authorizes the Coast Guard to establish and enforce vessel traffic services and systems, to establish water or waterfront safety zones, to prescribe minimum safety equipment requirements for structures on, in, or immediately adjacent to navigable waters, and to improve existing standards for the design, construction, alteration, repair, maintenance and operation of vessels carrying certain bulk cargoes.

Ever since the inception of a federal marine safety program, the U.S. Coast Guard and its predecessor agencies have sought to minimize the dangers to crews, passengers, vessels and cargoes in marine commerce, to the extent feasible without incurring an unreasonable economic penalty on the maritime industry, and indirectly, on the consuming public.

In more recent years, marine accidents have demonstrated hazard potentials that can reach far beyond the immediate threat to crew, passengers, vessel and cargo. Such accidents as the grounding of the TORREY CANYON near England, the structural failure at sea of the TEXACO OKLAHOMA, and the collision in New York harbor of the SEA WITCH and ESSO BRUSSELS, have dramatized the threat of major oil spills. Resulting ecologic and economic damage have led to nationwide and worldwide demands for prevention of such spills. A similar, yet potentially far more severe threat, is growing in the form of bulk shipments of hazardous

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[1] Code of Federal Regulations, Title 33, Navigation; and Title 46, Shipping.

chemicals needed as energy sources or for industrial production. Large spills of such materials near a populated area could pose a significant threat of fire, explosion, or toxic exposure to thousands of people. As of this writing, only one major marine accident of this type has occurred in the United States,[2] yet the risk of such a release is clearly present due to the carriage of dangerous chemicals in a marine transportation system in which serious vessel accidents continue to occur.

Concern with such accidents forces a qualitative revision in public regulatory thinking from a goal of minimizing marine accidents to assured prevention of at least certain types of accidents involving certain cargoes. This goal appears unrealistic in that the only known way to preclude accidents absolutely is to abstain from the activity from which they arise. Short of this, the safety of any operating system is threatened by mechanical failure, unusual environmental conditions (severe storm, tidal wave), and by human fallibility.

Public concern with these issues increases pressure on Coast Guard regulators to impose ever more stringent regulations and controls over all marine commerce, and especially over bulk liquid carriers. Several significant considerations must be balanced in the marine safety regulation process, however. In the Ports and Waterways Safety Act of 1972 (PL 92-340), which authorizes and encourages the promulgation of spill prevention rules and regulations, Congress also requires consideration of "(i) the need for such rules and regulations, (ii) the extent to which such rules or regulations will contribute to safety or protection of the marine environment, and (iii) the practicability of compliance therewith, including cost and technical feasibility."

In addition to these legislated considerations, the Coast Guard cannot ignore the fact that much of the foreign commerce in the United States is carried in foreign vessels. U.S. Maritime Administration data from 1974 indicates that only 6% of U.S. petroleum imports and exports are carried in U.S. flag vessels; 94% are carried in foreign vessels.[3] Although the U.S. Coast Guard can unilaterally influence the requirements for foreign vessels entering U.S. ports, the more desirable way to influence the global problem of maritime spill risks is through international maritime cooperation. Toward this end, the U.S. Coast Guard is very active in the U.N.-sponsored Intergovernmental Maritime Consultative Organization (IMCO). Improvements in maritime safety worked out by various specialized subcommittees of IMCO, when ready for implementation, are submitted to the full body for vote. Approved IMCO resolutions come into effect when ratified by a sufficient number of governments of the member nations. As may well be expected, this international approach is considerably slower than unilateral action.

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[2] The explosion of a cargo of ammonium nitrate at Texas City, Texas, in 1947, killed approximately 300 people.

[3] U.S. Congress, Office of Technology Assessment, "Oil Transportation by Tankers: An Analysis of Marine Pollution and Safety Measures." (Washington, D.C.: Government Printing Office, July 1975.)

Within the United States, various groups have various valid and partially conflicting interests in marine safety and spill prevention. Parallel situations exist in all advanced maritime nations of the free world. These groups include:

- Ship and barge owners, operators
- Marine labor unions
- Marine insurers
- Vessel classification societies
- Shippers of various cargoes
- Trade associations
- Professional/engineering societies
- The Congress of the United States
- Federal agencies involved with the maritime subsidy program, environmental protection, other transportation modes, foreign relations, and national defense
- State and local governments in areas served by vessel commerce
- Environmental action groups
- The U.S. public as consumers of products carried in marine commerce
- The U.S. public as persons at risk from damaging effects of hazardous/polluting substance spills
- The U.S. public as investors in various corporations whose profitability may be affected by the safety and efficiency of marine transportation. (These investments include pension funds, life insurance, and bank investments, as well as individual investments.)
- Portions of the scientific and academic communities involved in marine technology.

The total set of considerations/interests involved must be weighed and balanced to arrive at a suitable set of marine safety regulations and operational controls, subject to scientific and technical uncertainties regarding the safety effectiveness of potential actions, the consequences of marine spills, and the potential economic impacts.[4]

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[4] An excellent overview of the marine safety regulatory process can be gained from "Final Environmental Impact Statement: Regulations for Tank Vessels Engaged in the Carriage of Oil in Domestic Trade." (Washington, D.C.: U.S. Coast Guard, 15 August 1975.)

THE OPERATIONAL OBJECTIVE

Simply put, the objective of the federal government in U.S. marine commerce is to provide a legislative and regulatory environment that will promote public/environmental safety, high economic productivity, and equitable interests of many segments of the U.S. public.

Within the overall federal objective, the U.S. Coast Guard objective is to provide the most cost-effective program of marine safety and environmental protection possible. This leads to the question which necessitates the research reported here: How is the Coast Guard to know whether its program — and individual regulations within that program — are cost-effective?

Toward answering this question, the U.S. Coast Guard Office of Merchant Marine Safety completed in 1968, "A Study of the Costs, Benefits, and Effectiveness of the Merchant Marine Safety Program."[5] In general terms, that study concluded that a persuasive case could be made for the proposition that the United States benefits from having a federal marine safety regulatory program. It also showed that except in rare cases, no quantitative assessment is possible of the extent to which any specific safety action is effective in reducing the risks of marine accidents. In addition to continuing internal efforts to measure the cost-effectiveness of its program and specific regulations, the Office of Merchant Marine Safety also referred the problem to the then newly-formed Coast Guard Office of Research and Development. The requesting document stated, "In order to evaluate the effect of changes in regulations and requirements, a method of examining these changes in respect to the reduction of casualties or minimizing effects is desirable."

THE NEED FOR EXPERIMENTATION AND SCIENTIFIC METHOD

The field of safety has tended to lack a structured discipline until recent years. Lacking a discipline in which specifically defined training is accepted as a prerequisite to expertise, anyone who so chooses may consider himself knowledgeable about safety and about the effectiveness of safety measures. As a result there tend to be many bromides that are readily accepted on a superficial rationale. "Speed kills" oversimplifies problems of speed consistency among nearby vehicles/vessels, matters of designed efficient speed envelopes, effects of changing environmental conditions, and controllability aspects of the vehicle/vessel across certain speed thresholds. It has been commonly accepted by admiralty courts that, in the event of potential collision, vessels should reduce speed drastically while conducting any maneuver to avoid. In some situations, this may be valid; in many others, it is not only incorrect, but positively disastrous. In general, the fastest way for a displacement vessel to reduce velocity along an initial vector is to turn with hard rudder at full ahead throttle. Provided adequate room is available to execute such a maneuver safely, it should be employed more often.

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[5] U.S. Coast Guard, "A Study of the Costs, Benefits, and Effectiveness of the Merchant Marine Safety Program." (Springfield, Virginia: National Technical Information Service AD-780671, May 1968.)

Similar examples include:

- A common faith in computerized "collision avoidance radar systems" to accomplish what their name implies. In fact, such systems are of no value whatsoever in the greatest majority of collision instances, as is demonstrated in a later section of this report.

- A Congressional mandate to improve the maneuverability of tank vessels. Aside from stopping ability addressed above, greater maneuverability would include faster rate of turn. This would be beneficial if only the rates of turn of "innocent" vessels in a collision situation were improved. Because the innocent or offending vessel cannot be predicted, increased rates of turn could do more harm than good by decreasing the response time available when a more "maneuverable" offending vessel turns into the path of another vessel. See the discussion of this subject in the sections of this report relating to scenario model results.

- A common belief that a segment of the population is inherently "accident prone," whereas no scientific evidence of an inherent characteristic as is commonly meant by this term can be found. (This excludes situations where a job demanding muscular strength or keen eyesight may not be safe for persons lacking such strength or sight.) Accident proneness is now more commonly considered to be temporary and situational.

In the past, the public has been more willing than it currently is to accept the judgments of safety regulators who, even if not "safety" experts in any definable sense, were extensively knowledgeable about the technical disciplines relating to the fields they regulate. Now, and increasingly, various segments of the public insist directly, through the courts, or through their elected representatives that safety regulators, such as the Coast Guard, justify their decisions to apply, or not to apply, a proposed rule. In very many cases, an alternative body of experts in marine-related disciplines can be found to build a substantial case suitable to the desired position.

It is no longer enough for the Coast Guard or its challengers to decide subjectively on needs for marine regulation. Measures of probable effectiveness and expected benefits are now desired, measures derived from directly observable data.

This measurement need implies applying scientific methods to the actual issues of marine regulatory management to the extent feasible. Any such feasibility is relatively new; it must be built and expanded, as in any other science, by the long, slow, gradual process of theorizing, designing experiments to test the theories, conducting the experiments, revising the theories, and so forth. The weaknesses of the fledgling safety discipline discussed above exemplify the tendency to formulate and accept theories without empirical confirmation. A parallel process in safety management has been to compile huge "data bases" of accident data, which then lie fallow and unpatterned by

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rational analysis. Both situations are "unscientific." The process of accumulating scientific knowledge, as Margenau explains,[6] involves the formulation of rational (logical, deductive) theories, the establishment of "rules of correspondence" between the theories and the real world, and testing whether the observations of the real world confirm or disprove a theory. In the most rigorous sense, no theory can be proven true, or validated. It can, however, through proper experimentation be invalidated. A theory can be considered valid only after repeated conduct of experiments which, by their design, appear capable of proving the theory invalid. If such invalidation constantly fails to occur, then the theory may be tentatively accepted as valid.

PROBLEMS OF EXPERIMENTAL DESIGN

One theory of marine safety in the mid-1950s was that a significant cause of collisions was the lack of adequate sensors for determining the presence of other vessels. Accepting this theory uncritically, radars were extensively installed on vessels. Over subsequent years it was noted that vessels with radar were involved in collisions about as frequently as vessels without radar. In fact, certain cases indicate that the availability of radar fostered a false sense of security, thus contributing to what has been termed "radar-assisted collisions."

What happened here was that a theory was formulated, together with rules of correspondence to the real world, an "experiment" was conducted, and the theory that the availability of marine radars would substantively reduce collisions was (at least in that simple form) conclusively invalidated.

The experimental design in this case left a great deal to be desired. One would have liked to conduct the experiment without endangering ships, cargoes, and lives. One would have liked to avoid the extensive costs associated with the installation of thousands of radars if they are ineffective or worse. One would have liked the experiment to be concluded more quickly so that revisions to the theory and the search for more effective measures could be started sooner.

To be precise, the "experimental design" for the evaluation of radar was poorly conceived; it lacked definitive criteria for acceptance/rejection of the theory at the outset, desirable criteria of

- Objectivity
- Valid inference, and
- Repeatability of the experiment.

Lacking criteria of a general scientific methodology in marine safety, the maritime industrial complex has been preparing to conduct a similar experiment on a slight revision to the radar efficacy theory. "Collision avoidance

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[6] Henry Margenau, The Nature of Physical Reality: A Philosophy of Modern Physics, especially "Empirical Confirmation," Chapter 6. (New York: McGraw-Hill, 1950.)

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radar systems" are being installed on vessels voluntarily, are required in the U.S. subsidy program, and have been proposed for all vessels over 10,000 gross tons as a Coast Guard regulation. A more desirable "experimental design" to test their efficacy cheaply and quickly is described herein.

The same line of argument used above can be turned around on the advocate of scientific experiment, however. It is endemic to scientific experimentation that experiments disprove cherished theories, involve elaborate work and expense only to prove inconclusively, or prove that which was amply obvious before the experiment. Scientific method and sound experimental design are not without pitfalls; they merely define the only known path to the accumulation of sound knowledge in the long run.

Safety management science may well follow in the path of the science of teaching as described by Campbell and Stanley:

> "The initial advocates assumed that progress in the technology of teaching had been slow just because scientific method had not been applied: they assumed traditional practice was incompetent, just because it had not been produced by experimentation. When, in fact, experiments often proved to be tedious, equivocal, of undependable replicability, and to confirm prescientific wisdom, the overoptimistic grounds upon which experimentation had been justified were undercut, and a disillusioned rejection or neglect took place.
>
> This disillusionment was shared by both observer and participant in experimentation. For the experimenters, a personal avoidance-conditioning to experimentation can be noted. For the usual highly-motivated researcher the nonconfirmation of a cherished hypothesis is actively painful. As a biological and psychological animal, the experimenter is subject to laws of learning which lead him inevitably to associate this pain with the contiguous stimuli and events. These stimuli are apt to be the experimental process itself, more vividly and directly than the 'true' source of frustration, i.e., the inadequate theory. This can lead, perhaps unconsciously, to the avoidance or rejection of the experimental process. If, as seems likely, the ecology of our science is one in which there are available many more wrong responses than correct ones, we may anticipate that most experiments will be disappointing. We must somehow inoculate young experimenters against this effect, and in general must justify experimentation on more pessimistic grounds—not as a panacea, but rather as the only available route to cumulative progress. We must instill in our students the expectation of tedium and disappointment and the duty of thorough persistence, by now so well achieved in the biological and physical sciences. We must expand our students' vow of poverty to include not only the willingness to accept poverty of finances, but also a poverty of experimental results.

More specifically, we must increase our time perspective, and recognize that continuous, multiple experimentation is more typical of science than once-and-for-all definitive experiments. The experiments we do today, if successful, will need replication and cross-validation at other times under other conditions before they can become an established part of science, before they can be theoretically interpreted with confidence. Further, even though we recognize experimentation as the basic language of proof, as the only decision court for disagreement between rival theories, we should not expect that 'crucial experiments' which pit opposing theories will be likely to have clear-cut outcomes. When one finds, for example, that competent observers advocate strongly divergent points of view, it seems likely on a priori grounds that both have observed something valid about the natural situation, and that both represent a part of the truth. The stronger the controversy, the more likely this is. Thus we might expect in such cases an experimental outcome with mixed results, or with the balance of truth varying subtly from experiment to experiment."

THE SPECIFIC RESEARCH PROBLEM

The research problem involved here is how to provide effective ways of measuring, in the words of the Ports and Waterways Safety Act:

"(i) the need for such rules and regulations

(ii) the extent to which such rules or regulations will contribute to safety or protection of the marine environment, and

(iii) the practicality of compliance therewith, including cost and technical feasibility."

Direct quantitative measures of "safety" are not available; however, a common approach is to define "risk" as non-safety and to measure risk. Measures of risk reduction are thus equivalent to measures of safety improvement.

The premise adopted for this research effort is based on an equation of risk (hence safety) measurement:

$$R_1 + \Delta R = R_2, \text{ (}R_1 \text{ compared to } R_A\text{)}$$

where

R_1 = level of risk assessed prior to a change in the marine transportation system

ΔR = the positive, negative, or zero change in risk associated with the change in question

R_2 = the level of risk expected after the change, and

R_A = the level of risk acceptable to the public considering costs (economic impact) and the balancing of the full range of diverse considerations and interests in marine safety.

Taking a position similar to that of Turner in a National Academy of Sciences Forum on safety decision-making with respect to food and drug regulation, R_A is rejected as a proper subject for scientific and technical measurement.[7] The societal attitudes toward risk acceptance are a multifaceted and highly dynamic set, capable of expression at any point in time through the political process of written and oral comment on proposed legislation or regulation. This process exposes and allows resolution of the multiple facets of public interest. Simply put, no scientist or technocrat has the right to tell the public what risks they will or should accept. It is up to the public to tell the government what risk should be accepted with regard to each crucial decision. The broader the public participation in this process, the finer the relevant measure of risk acceptability.

Within the remaining terms of the equation, measurement of R_1 may be termed "risk measurement" and measurement of ΔR may be termed "risk management" (or more properly, risk reduction effectiveness measurement). R_2 is merely the algebraic sum of $R_1 + \Delta R$.

Given the current state of knowledge of safety measurement (or risk analysis), quantitative measurement of either R_1 or ΔR is a difficult, expensive, and slow process, and the two measurements require separate efforts. For example, in the recent Draft Reactor Safety Study, which consumed three million dollars, 50 man-years, and two calendar years for a set of R_1 measures, the authors note that their study does not provide suitable and adequate information on which to base decisions regarding changes in commercial reactor safety systems.

> "This study, using an overall methodology directed toward risk assessment, has developed new insights that contribute to a better understanding of reactor safety. However, many of the techniques used were developed and used only for the purpose of overall risk assessment and are not directly applicable for optimizing safety designs or evaluating the acceptability of specific designs or reactor site location. Although the techniques developed in the study may someday be useful for such purposes, considerable additional development is needed before they can assist effectively in safety decision making.
>
> Decision making processes in many fields, and especially in safety, are quite complex and should not lightly be changed.

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7 James S. Turner, "A Consumer's Viewpoint" in How Safe is Safe?: The Design of Policy on Drugs and Food Additives (Washington, D.C.: National Academy of Sciences, 1974), pp. 13-22.

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This is especially true where a good safety record has already been obtained, as is so far true for nuclear power plants. The use of quantitative techniques in decision making associated with risk is still in its early stages and is highly formative. It appears that for the near future considerable additional development is needed in quantitative techniques before they can be used effectively in safety decision making processes."[8]

Agreeing that considerable additional research is needed to establish the applicability of quantitative techniques to safety decision-making processes, it was decided to focus on the ΔR term. To the extent that a public demand exists for reducing the risks of marine accidents/spills, that is sufficient evidence that the perceived value of R_1 exceeds R_A and that Coast Guard action should be taken, if technically and economically feasible. Quantification of R_1 would express "the need for such rules or regulations" in more concrete terms, but would not affect the existence of such a need.

Measurement of ΔR specifically addresses "the extent to which such rules or regulations will contribute to safety or protection of the marine environment" and thus more directly attacks the program management issue.

At this point, we may define $R = P \times C$; that is, risk is measured as the probability of an undesired event times the consequences of that event. More succinctly, risk is the probability distribution of damage from an activity. As a point estimate, risk is the expected value of unfavorable consequences.

It follows, then, that ΔR may be measured in three ways:

$$\Delta R = \Delta P \times C$$

$$\Delta R = P \times \Delta C$$

$$\Delta R = \Delta P \times \Delta C,$$

depending on the focus on change in capability to prevent accidents, capability to mitigate the consequences of accidents, or both.

It is assumed that, given a choice, it is preferable to prevent accidents in the first place and that mitigation of accident effects is a secondary objective existing only to the extent that attempts to prevent accidents are unsuccessful. Because accident prevention programs do not tend to be 100% effective, both the first and third measures of ΔR are desirable. The priority should be on the first.

It is not even minimally adequate to measure the effectiveness of marine safety regulations alone. Potentially very effective safety measures can have high societal costs. Assessments of the social, political, economic, and environmental impacts of advances in technology, including marine safety technology, are being attempted, for example, by the U.S. Congress Office of

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[8] U.S. Atomic Energy Commission, Summary Report, Draft Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. (Washington, D.C., August 1974.) Note: This terminology was deleted from the final version of the report.

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Technology Assessment. Such analysis is beyond the capability of the Coast Guard's current research program. As a subsidiary measure, the Coast Guard is attempting to measure the economic impact of its regulations in the spirit of President Ford's wishes to keep the federal government "off the backs and out of the pockets" of the American public.

The logic applied above leads to definition of the Risk Management System development program depicted in Figure 1. Related, but technically separate developments are needed to

- Measure the safety effectiveness of Coast Guard changes to the maritime transportation system
- Assess the consequences in terms of death, injury, and property or environmental damage of marine accidents which may be prevented
- Evaluate the economic impact of marine safety rules or regulations
- Integrate all such measures with respect to a proposed rule or regulation to predict its cost-effectiveness and follow through on recently implemented rules and regulations to assess the cost-effectiveness actually achieved.

Within the context of this overall Risk Management System development concept, this report explains the research and results with respect to the first block of the diagram. To the extent that the research has been successful, it provides methods of quantitatively measuring the change in marine accident probability associated with specific rules or regulations. For the many cases in which the consequences of a marine accident, if it occurs, are unaffected by an accident preventative measure, then the ΔR is proportional to ΔP, and thus the methodologies do produce estimates of ΔR, definable as "the extent to which such rules or regulations will contribute to safety or protection of the marine environment."

In the process of developing the methods reported here, it was necessary to identify the relative contributions to risk posed by various parameters of the maritime operating system. To the extent that such efforts have been successful, these methods provide a supportive input to the process of determining "the need for such rules or regulations."

Determination of probable consequences of marine spills is not addressed here, nor is "the practicality of compliance (with such rules or regulations), including cost and technical feasibility." Technical feasibility is normally assessed by the Coast Guard regulatory staff, supported in part by other research and development projects in the commercial vessel safety research and development program.

Research in consequence assessment and economic impact assessment are separate, but related efforts in Risk Management System development.

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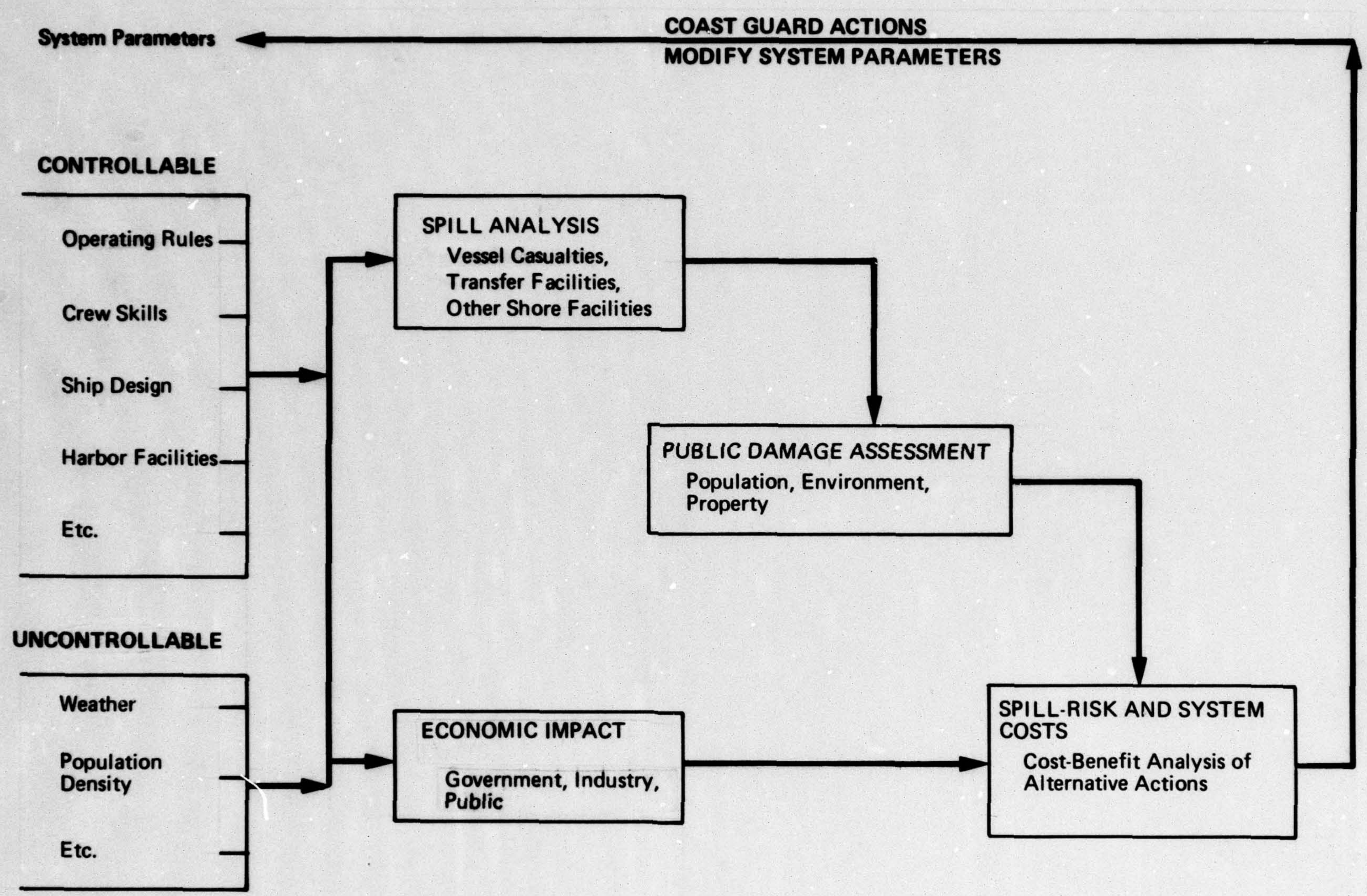

FIGURE 1. RISK MANAGEMENT—THE SYSTEMS APPROACH

One final comment is necessary to complete the definition of the scope of the research problem addressed in this report. There are numerous types of marine accidents which may result in spills of oil or hazardous substances. To a certain extent each accident type may require some specialized methodology. Commercial vessel collisions (between two underway vessels) were selected for this study. Of the two methodologies developed here, one appears generally applicable to all marine accident types (as well as to many other safety and other social science problems); the other method is specific to marine collisions, with some possible adaptability to collisions with fixed objects (rammings) or to groundings.

ORGANIZATION OF THE REPORT

This introduction, Part 1 of the report, has provided background information on the operational problems that call for further research into marine safety parameters and means of evaluating risk reduction, or safety improvement measures. The need for experimentation and some of the general problems of experimental design have been discussed. "Risk management" has been put forth as a concept from which a productive program of safety research can be developed and the terms of a risk equation have been stated. Within this broad research program outline, the place of the research reported herein has been identified and the limits of scope of this effort have been stated.

Parts 2 and 3 of this volume document the development and demonstration of two methods by which the potential impact on risk (ΔR as previously defined) of selected Coast Guard safety initiatives can be estimated. The first part describes the development and demonstration of a Quasi-Experimental Method (QEM) for quantitative analysis of narrative records to estimate risk reduction potential by regulatory actions. The second part treats the Scenario Model for estimation of spill risk associated with probability of vessel collision. Volume II reports the results of an examination of the Pollution Incident Reporting System (PIRS) data base.

PART 2:
QUASI-EXPERIMENTAL METHOD (QEM) DEMONSTRATION

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PART 2: QUASI-EXPERIMENTAL METHOD (QEM) DEMONSTRATION

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I. DESCRIPTION OF THE METHOD

GENERAL

The development background of the Quasi-Experimental Method (QEM) is detailed in a previous report on this project.[1] The purpose of this section is to summarize the fuller explanation of the earlier report so that this current report will stand alone. The QEM is an objective, scientific means of analyzing narrative material. It is believed to apply to a wide range of problem areas in governmental operations. Specifically it should apply to the analysis of any system wherein narrative materials comprise a significant portion of the available data. In the present case, it has been applied to a series of analyses using the marine casualty report files at U.S. Coast Guard Headquarters. The basic difference between the QEM and other previous examinations of narrative information is the control of individual judgment bias.

HISTORY

Faced with the problem of examining effective measures for reducing ship collisions, the QEM was developed as a means of quantitatively and objectively evaluating data sources in the form of Coast Guard ship collision histories. The use of historical data was based on principles and methods suggested by Campbell and Stanley for research in teaching and education.[2] In the field of education, as is true in many others, it is often impossible to set up the control groups necessary for true scientific experimentation. Campbell and Stanley discuss a series of experimental and quasi-experimental

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[1] Spill Risk Analysis Program: Phase II Methodology Development and Demonstration. Operations Research, Inc., Technical Report 840, August 1974. Coast Guard Report No. CG-D-15-75. NTIS Catalog No. AD-7585026.

[2] D.T. Campbell and J.L. Stanley, Experimental and Quasi-Experimental Design for Research. (Chicago: Rand-McNally, 1963.)

designs along with a discussion of the factors which might jeopardize the validity of any experiment. The designs suggested for those situations where control groups cannot be identified are designated *"quasi-experimental."* Quasi-experiments can produce results as valid as true experiments if careful consideration is given to the sources which might produce invalidity when the design is being formulated. For the viewpoint of the final interpretation of an experiment, every experiment is imperfect in that experimental results "probe" rather than "prove" a theory. A good hypothesis is one that has survived extensive probing. The hypothesis is never "accepted", it can only be "rejected" or "fail to be rejected." The validity criteria outlined by Campbell and Stanley can make an experimenter more aware of the residual imperfections in his design so that he will also be aware of the possible competing interpretations of his data. These points, which are adapted from the Campbell and Stanley article, were applied in the design of the QEM described and demonstrated in this report.

ANALYTIC APPROACH

Faced with a set of problems whose solution should be related to the data available in various U.S. Coast Guard casualty files, project analysts at ORI set about the task of designing an experiment which would reduce the narrative information in the field in a reliable manner, to data elements that could be treated statistically. The resulting analytic structure was the QEM. A description of a representative QEM experiment follows.

The first step in the analysis of Coast Guard collision reports was the selection of a small sample of representative reports which were closely examined to determine structural relationships within various collision scenarios. From this initial review, a logical model of a normal, accident-free encounter between two ships developed. This model covers the following:

1. Both vessels are operated in a safe and prudent manner with respect to conditions at hand.
2. Both vessels detect each other at a comfortable distance and observe that their course and speed will bring them into close proximity to one another in the near future.
3. Both vessels agree on an intended passing strategy.
4. Neither vessel encounters any unexpected difficulties (e.g., sudden change in wind and current, equipment failure, or human error) in executing intended maneuvers.
5. Therefore, both make necessary maneuvers to achieve a safe passing.

If any of the first four conditions were not achieved, the encounter would become increasingly hazardous.

(48)

Using the logical model as a foundation, a series of specific collision event sequence diagrams was developed. An example of this type of diagram is shown in Figure 1. From the information derived from the collision event sequence diagrams, a detailed collision safety analysis logic tree (SALT) was constructed. The SALT showed the logical (or illogical) paths which two ships may follow on their way to a collision. The highest level of the SALT diagram is illustrated in Figure 2. This illustration is taken from the previous report,[3] where the SALT is explained in detail.[4]

With conditions and decision/action possibilities defined for typical casualty situations, the potential efficacy of various means of avoiding the casualty may be assessed with greater clarity. The next step in the methodology was to develop Casualty Analysis Gauges" (CAGs) for that purpose. Each CAG, formulated with the assistance of the SALT, consists of a series of questions designed to establish whether the conditions and actions/decisions possible during the event described in a casualty record were such that a particular anti-collision measure could have been effective. Four CAGs were developed during this research. They are presented in Appendices A, B, and C at the end of this volume.

The term "gauge" is used because the series of questions helps in regulating the analysis of the casualty record. The use of a CAG assures that the same questions, determined to be pertinent in preliminary analysis of randomly selected casualty records, are asked consistently. Thus the use of the CAG eliminates a major source of judgmental subjectivity that can intrude in analysis of narrative records—i.e., the error introduced by varying parameters used to draw conclusions from the records.

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[3] ORI, August 1974, op. cit.

[4] During the formal oral presentations of the results of this project at U.S. Coast Guard headquarters, a question was raised concerning the potential use of the SALT model as a basis for improving vessel casualty investigation and reporting procedures. A small investigation into this potential was initiated. The findings of this study were that the SALT method, as presently configured, is unsuitable as a model for casualty investigations and reports due to the lack of an inherent sequential structure. The project led to an unscheduled small-scale review of current safety analysis techniques which concluded that the most likely foundation for an improved casualty investigation and reporting model would be provided by combining features of the Relative Accident Probability (RAP) technique described in ORI Technical Report 407, Preliminary Analysis of the MK 48 Exploder (although this report is classified, the technique is not classified, and can be thoroughly explained by any of the three authors employed at ORI), and the Multiple Events Sequencing (MES) method outlined by Ludwig Benner of the National Transportation Safety Board in his article, "Accident Investigations: Multiple Events Sequencing Methods," Journal of Safety Research, June 1975. A report of this evaluation, Feasibility of Using a Logic Tree Methodology in Reporting Marine Accidents, ORI Technical Memorandum 110,76, is included as Appendix G of this volume.

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SPECIFIC COLLISION EVENT SEQUENCE
(Case #21644)

SHIP 1

1. PILOT ORDERS SHIPS TO MAINTAIN POSITION IN CENTER OF CHANNEL

2. PILOT, MASTER, OR MATE DETECTS TARGET ON RADAR.
   - A. PILOT, MASTER, MATE DETERMINES TARGET TO BE JUST INSIDE THREE-MILE RANGE.
   - B. PILOT, MASTER DETERMINE LIGHT TO BE SLIGHTLY TO PORT OF HEADING DASHER.

3. PILOT, MASTER SEE WHITE LIGHT.
   - A. PILOT, MASTER ESTIMATE RANGE TO BE 2 1/2 MILES.
   - B. PILOT, MASTER DETERMINE LIGHT TO BE SLIGHTLY TO PORT.

4. PILOT ORDERS SPEED REDUCED TO 1/2 AHEAD.
   - A. ENGINE ROOM CARRIES OUT ORDER.

5. PILOT AND MASTER AGREE THAT MOVEMENT OF THE LIGHT AND RADAR PICTURE INDICATE TARGET TO BE CROSSING CHANNEL TO THEIR RIGHT, i.e., ACROSS THE BOW OF THEIR SHIP. *SEE FIG. F.2*

6. PILOT AND MASTER MAKE DECISION ON STARBOARD TO STARBOARD PASSAGE. PILOT AND MASTER DECIDE NOT TO ATTEMPT COMMUNICATIONS. *SEE FIG. F.5*

7. PILOT ORDERS SHIP'S COURSE ALTERED SHARPLY TO PORT IN ORDER TO FAVOR THE LEFT DESCENDING BANK.
   - A. HELMSMAN CARRIES OUT ORDER.

8. PILOT, MASTER AND LOOKOUT SEE BOTH RANGE LIGHTS, AND THE RED LIGHT OF THE OTHER SHIP.
   - A. PILOT, MASTER, LOOKOUT ESTIMATE RANGE TO BE ABOUT 1/2 MILE.

9. PILOT ORDERS TWO BLASTS SOUNDED.
   - A. TWO BLASTS ARE SOUNDED.
   - B. PILOT REMARKS NO RESPONSE IS HEARD.
   - C. PILOT ORDERS ENGINE STOPPED.
   - D. ENGINE IS STOPPED.
   - E. PILOT ORDERS LEFT FULL RUDDER. *SEE FIG. F.4*
   - F. HELMSMAN EXECUTES LEFT FULL RUDDER.
   - G. PILOT DECIDES NOT TO STOP SHIP. *SEE FIG. F.4*

10. PILOT ORDERS DANGER SIGNAL SOUNDED.
    - A. PILOT ESTIMATES RANGE AT 1/4 MILE.

11. PILOT ORDERS ENGINE ASTERN.
    - A. ENGINE IS PUT ASTERN.

12. COLLISION.

SHIP 2

1. PILOT ORDERS SHIP TO MAINTAIN POSITION FAVORING THE LEFT DESCENDING BANK.

2. PILOT STATION WATCHMAN INFORMS PILOT OF OTHER SHIP'S PRESENCE.

3. PILOT, MASTER DETECT SHIP 1 ON RADAR.
   - A. PILOT, MASTER ESTIMATE RANGE AS 2 1/2 - 3 MILES.

4. PILOT, MASTER DETECT SHIP 1 VISUALLY.
   - A. PILOT, MASTER, LOOKOUT ESTIMATE RANGE AT 1 1/2 MILES.
   - B. PILOT, MASTER NOTE THAT SHIP 1 APPEARS TO BE IN THE CENTER OF THE CHANNEL.

5. PILOT ORDERS ONE BLAST.
   - A. PILOT ESTIMATES RANGE AS 1 MILE.
   - B. SIGNAL IS EXECUTED.
   - C. PILOT ORDERS COURSE ALTERED TO STARBOARD. *SEE FIG. F.4*
   - D. HELMSMAN ALTERS COURSE TO STARBOARD
   - E. PILOT CALLS OTHER SHIP ON CHANNEL 13.
   - F. PILOT REMARKS THAT HE DID NOT RECEIVE AN ANSWER TO HIS WHISTLES OR RADIO CALL. *SEE FIG. F.8*

6. PILOT ORDERS ONE BLAST AGAIN.
   - A. PILOT ESTIMATES RANGE AS 1/2 MILE.
   - B. SIGNAL IS EXECUTED.
   - C. PILOT ORDERS FURTHER COURSE CHANGE TO STARBOARD.
   - D. HELMSMAN ALTERS COURSE TO STARBOARD.
   - E. PILOT CALLS SHIP 1 ON CHANNEL 13.
   - F. PILOT REMARKS HE HEARD NO RESPONSE TO WHISTLE OR RADIO. *SEE FIG. F.8*

7. PILOT, MASTER, LOOKOUT SEE SHIP 1 CHANGING COURSE TO ITS PORT (ACROSS THE BOW OF SHIP 2).
   - A. PILOT, MASTER ESTIMATE RANGE TO 1/5 MILE.
   - B. PILOT, MASTER SEE SHIP 1's GREEN SIDELIGHT.
   - C. PILOT HEARS DANGER SIGNAL FROM SHIP 1.

8. PILOT ORDERS RUDDER HARD TO PORT.
   - A. HELMSMAN EXECUTES ORDER.
   - B. PILOT ORDERS ENGINES STOPPED.
   - C. ENGINES ARE STOPPED.

9. COLLISION.

90%

FIGURE 1. COLLISION EVENT SEQUENCE DIAGRAM EXAMPLE

50

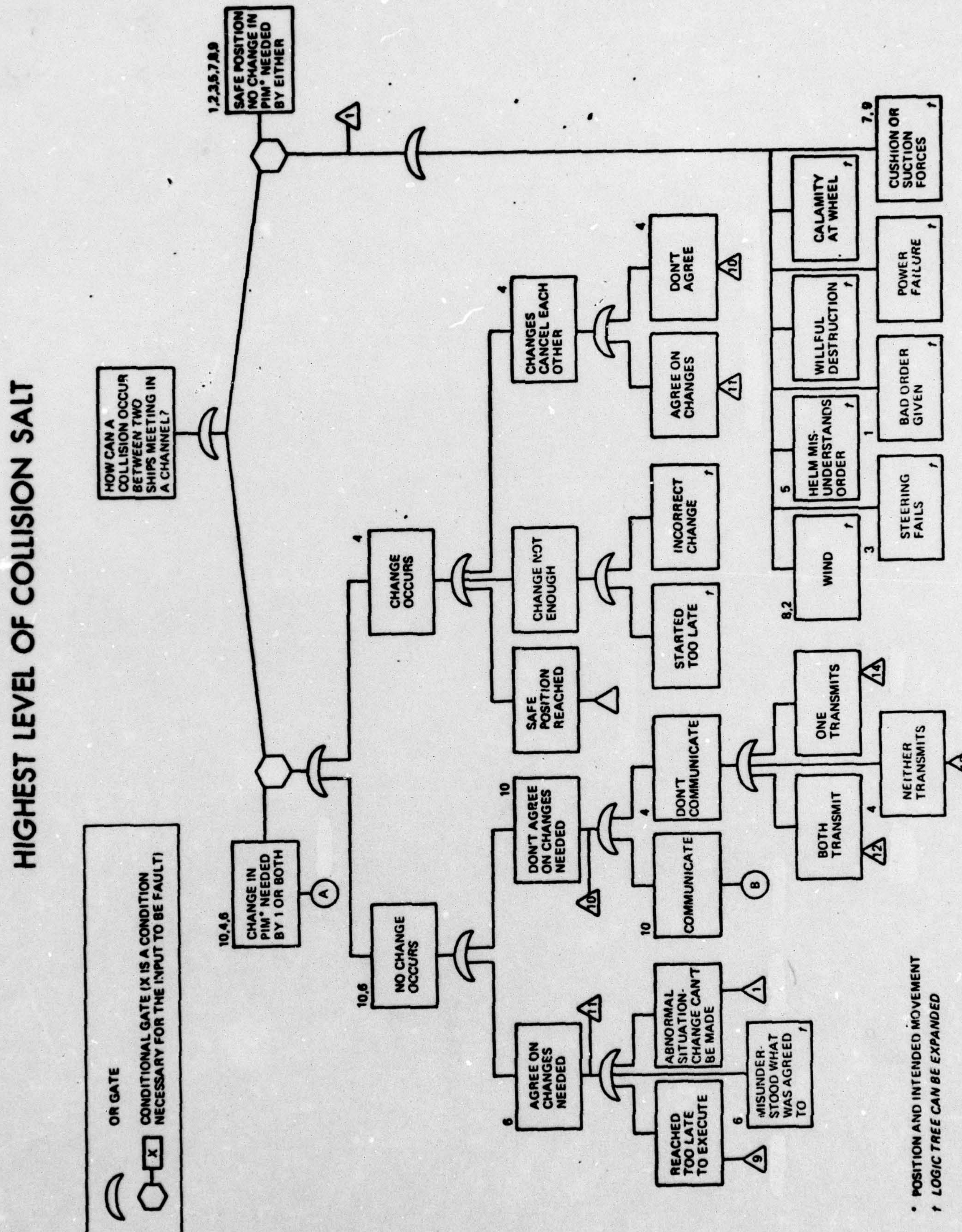

FIGURE 2. ILLUSTRATION OF COLLISION SALT

51

90%

Clearly, even though the parameters for consideration in the analysis are predetermined and used in all cases, they may not be the optimal set. Most basically, the choice is constrained by the types of information recorded in the narrative, since it defeats the purpose to select parameters that cannot be "observed directly" in the records.

The existence of a CAG and its antecedent SALT allows the content validity of the analysis to be evaluated. The appropriateness of the questions in the CAG should be logically evident to persons knowledgeable of the field when the questions are considered in relation to the SALT which describes possible sequences of conditions and actions in a typical situation with collision potential. In the absence of a measurable criterion, no stronger support is available for what might be called the "external validity" of the analysis—i.e., the degree to which it determines what it is intended to determine about actual operations and events.

Record sampling admits statistical testing to establish the degree of what might be called the "internal validity" of the analysis. Two of the three QEM demonstrations reported herein used a sample of collision records; the statistical procedures employed are described in the sections on those demonstrations.

The CAG also provides a means of checking the reliability of the analysis. In the research reported here, two analysts independently applied each CAG to the records. The degree of correlation in their answers provides a reliability measure. The four CAGs developed were applied to a total of 717 collision reports. Differences of opinion were resolved, in joint reexamination of the report. There were a few instances in which a difference could not be resolved, but a correlation of at least 0.95 was obtained in each application of a CAG.

A further advantage of the application of QEM outlined here is that, once the CAG has been constructed and validated against the case sample by trained and experienced professional marine analysts, it can be applied by inexperienced researchers at a considerable saving in cost, without impairing the reliability, provided that reliability checks are instituted.

SOME CAUTIONARY NOTES

While this form of QEM has many advantages, it uses what has been called "retrospective analysis." The analysis consists essentially of looking at past history and trying to deduce "what might have happened if ..." Carefully done, this is a useful way of proceeding. There are, however, some potential dangers in retrospective analysis. Retrospective analysis obviously is limited to such parameters as were present in historical operations <u>and</u> were reflected in the marine accident reports. The influences of unreported parameters and the relevance of analysis results to the future remain to be assessed separately, if that is possible. It is easy to let one's thinking become wishful thinking and to go from "might" to "will," that is, from possibilities to actualities. No amount of sophisticated mathematical analysis will change a "might" to a "will." Researchers using the QEM must be constantly alert to the possibility of alternative explanations and to the problems of logical inconsistencies and oversights in the construction of QEM criteria.

Another problem area is the manner in which the complexity of the QEM (and the time required for report review) increases as the breadth of the analytic problem area expands. The three problems addressed in this report, in increasing order of complexity, are bridge-to-bridge radio communication regulations, collision-avoidance system alternatives, and collision causes. The CAG for each of these requires 12, then 16, and finally 30 questions. It was found that as the number of questions grows, the amount of time needed for report review tends to grow at a rate closer to a geometric, rather than a linear, progression. This indicates a continuing payoff for detailed initial analysis prior to the commencement of a large scale narrative review effort. This initial work should have as its goal the development of a logically robust and optimally short CAG.

A major problem is the fact that effectiveness predictions derived by the QEM are, unless adjustments are made, theoretical maximums which assume 100% reliability, applicability, and quality of utilization by marine personnel of the regulatory/safety standard change being evaluated. This results from the either/or categorization of casualty cases. Either the casualty absolutely could not have been prevented or it <u>might</u> have ben prevented by the change considered. Ideally, a safety initiative would prevent every casualty it is potentially capable of preventing. In the real world, however, even fine equipment fails; even well trained and experienced personnel sometimes err in using equipment and procedures; and anamalous conditions of the operating environment may defeat a normally safe system. The complex interaction of variables that may, in reality, determine whether a casualty is preventable defies the capabilities of quantitative retrospective analysis, let alone prediction, at least presently.

Adjustments of theoretical maximum effectiveness estimates toward more realistic values are always required and will be in the direction of lesser effectiveness. One means of adjusting the estimates was demonstrated in the analysis of bridge-to-bridge radiotelephone effectiveness. That was, however, a special case because the regulation being evaluated had been implemented and use of the system provided some, albeit limited, data on what might be called the failure rate. In general, pending further methodological advances, the upper limit provided by the theoretical maximum effectiveness must suffice as a reasonable basis for deciding the merits of a safety initiative.

Other problems which arise in the application of the QEM are of somewhat less importance, but must be addressed nevertheless. The fact that the information used in the analysis is limited to that contained in narrative reports applies to any methodology which might be used on these files. Recognizing that we are dealing with an ex post facto, limited set of data regarding each collision, we accept this restriction in exchange for the cost savings realized from not having to send researchers into the field. Where cases of conflicting evidence and statements of fact occurred within the reports, the QEM reviewers relied on the opinion and judgment of the USCG investigating officer since he presumably had access to information other than that contained in the written reports. In this context, it was interesting to note that, in a number of cases, the investigating officer's findings of fact differed from the facts as related by either of the parties to the collision.

II. DEMONSTRATION ANALYSES

The QEM methodology outlined in the last section has been demonstrated through application to three representative problems in the marine safety field. The problems differ in scope and direction, but all are representative of real issues facing Coast Guard decision-makers at the current time. The three problems addressed are:

- <u>Bridge-to-Bridge Radiotelephone Effectiveness</u>
  This analysis examined the effectiveness of a newly implemented regulation through a comparison of statistics before and after the 1 January 1973 date of implementation.

- <u>Collision-Avoidance Radar System Effectiveness</u>
  This analysis evaluated the potential gains through implementation of a proposed new regulation

- <u>Collision Causes</u>
  This was a problem-definition analysis directed to clarifying the sources of marine collision problems.

Procedures and results of each demonstration analysis are presented separately. Related findings from the other analyses are discussed. The collision cause analysis, in particular, was found to illuminate results from the other two.

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BRIDGE-TO-BRIDGE RADIOTELEPHONE EFFECTIVENESS

INTRODUCTION

In working towards its goal of vessel safety and the elimination of spills of polluting substances, the U.S. Coast guard, on 1 January 1973, initiated regulations incorporating the provisions of the Bridge-to-Bridge Radiotelephone Act.[1] This act has as its purpose "to provide a positive means whereby the operators of approaching vessels can communicate their intentions to one another." The new law requires most vessels to be equipped with a bridge-to-bridge radiotelephone capable of sending and receiving on channel 13. The law further states that while the vessel is being operated within U.S. waters, the radio will be tuned to channel 13, a listening watch will be maintained, and the vessel will answer if called on this channel. *The law does not require that bridge-to-bridge radiotelephone be used to establish passing agreements or make security calls*, although such use is permitted and clearly anticipated. However, the Coast Guard Regulation (Title 33, Code of Federal Regulations, Part 26) implementing the Bridge-to-Bridge Radiotelephone Act specifically states (26.04.b) that all vessels covered by this regulation "shall, when necessary, transmit and confirm, on the designated frequency, the intentions of his vessel and any other information necessary for the safe navigation of vessels." The determination of "when necessary" is left to the judgment of the individual vessel operators. Having promulgated these regulations, the Coast Guard now faces the problem of evaluating their effectiveness.

ANALYTIC DESIGN

The bridge-to-bridge radiotelephone regulation was evaluated by determining and comparing the percentages of past collisions that might have been prevented by the use of bridge-to-bridge radiotelephone before and after the legislation and Coast Guard regulation requiring the use of bridge-to-bridge

[1] Public Law 92-63, 4 August 1971.

radiotelephone. The determination of collision "preventability" was made from the collision reports in the casualty record files maintained by the U.S. Coast Guard, using a logical model developed by means of the Quasi-Experimental Method as summarized in the preceding section and described in detail in a previous report.[2]

Analytic Propositions

- An appreciable decrease in the percentage of bridge-to-bridge radiotelephone-preventable collisions in the years following the legislation/regulation would be indicative of their utility

- On the assumption that the near future will be similar to the recent past, the mean percentage of bridge-to-bridge radiotelephone-preventable collisions over the years following the legislation/regulation provides a good estimate of their potential effectiveness.

Period of Observation

Initially, fiscal years 1969 through 1972 were analyzed to test the methodology.[3] Since the Act was passed early in FY 1972, this 4-year period seemed appropriate to establish a baseline for the determination of change. However, relatively large differences were noted in the numbers of collisions judged preventable between FY 1969-1970, and FY 1971-1972. These findings indicated that years prior to FY 1969, as well as years following FY 1972, should be included. Thus the period of observation was extended to cover 11 years, from FY 1964-1974. (Collision reports for the years 1963, 1973, and 1974 were analyzed next, after the initial 4 years; those results are the subject of a separate, interim report.[4] The final period studied included FY 1964-1967; those results are reported for the first time herein.) The 11-year period provided a 5-year baseline prior to the first year of appreciable decrease in collisions preventable by bridge-to-bridge radiotelephone, and it provided 5 years for observation of the stability of the decrease.

Sample

A 30% random sample without replacement, was drawn from the reports of collisions each year in the period of observation. This was the largest sample feasible considering time and budget constraints. The sample included

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[2] Operations Research, Inc., Spill Risk Analysis Program: Phase II Methodology Development and Demonstration, Technical Report 840, 2 August 1974. Coast Guard Report No. CG-D-15-75. NTIS Catalog No. AD-785-026.

[3] Ibid.

[4] Operations Research, Inc., Spill Risk Analysis Program Interim Report E-1: Effectiveness of Bridge-to-Bridge Radiotelephone Regulations, 30 September 1974.

525 reports, of which 436 involved vessels currently required by the regulation to have bridge-to-bridge radiotelephone.

Analytic Procedure

The determination of "preventability" is made by using a casualty report to answer a rigidly structured set of questions, called a Casualty Analysis Gauge (CAG). (See preceding section on the methodology for discussion of the CAG.) If the casualty passes the gauge, then we say the casualty might have been prevented by the Coast Guard action under consideration. The objectivity of this process can be monitored by comparing the results of two independent researchers evaluating the same data. A high degree of objectivity and repeatability is essential if the results of the evaluation are to be used in regulatory decision-making. In consideration of the 11 years of casualty reports used in this analysis, two independent researchers studied 525 reports, of which 436 involved vessels affected by the Act. The researchers agreed on answers to 428 of these 436, for an agreement rate of 98%.

CAGs were developed to evaluate two possible regulatory initiatives which the Coast Guard might take in relation to bridge-to-bridge radiotelephone communications. These actions are as follows:

Action 1: Action which results in a requirement to use bridge-to-bridge radiotelephone to achieve all passing agreements.

Action 2: Action which results in a requirement to use bridge-to-bridge radiotelephone in attempting to determine the presence of other traffic whenever approaching a blind spot in a channel (security call).

The CAGs used for these actions are presented in Appendix A.

Statistical Treatment

The binomial distribution was used to establish the confidence limits on the sample determinations at the 95% significance level. Least-squares analysis was employed to examine trends in system use and problems in use.

Limitation of the Interpretation of Analysis Results

The questions in the CAG were formulated in such a way that a "yes" to all of them indicated that implementation of the action might have prevented the collision. This made the results easy to count, and it also made apparent that the judgments of preventability made in the CAG review related to a theoretical maximum effectiveness of the bridge-to-bridge communication system. There were instances in which yes answers were obtained to all CAG questions except that establishing whether the bridge-to-bridge radiotelephone was used (Questions 2 and 7, respectively, on the Passing Agreement and Security Call CAGs). That is, there were instances in which the analysis indicated that the

collision was preventable by the use of bridge-to-bridge radiotelephone; however, it was used and the collision occurred nonetheless. This indicates that some portion of the theoretical maximum effectiveness of the regulations requiring bridge-to-bridge radiotelephones can be expected to be offset by misuse of the system or by system failures such as saturation of the channel. The theoretically preventable collisions found to occur despite the use of the bridge-to-bridge radiotelephone were categorized unpreventable, as a means of reducing the estimates derived from the analysis so that they more accurately represent the realities of system use. It should be borne in mind, however, that despite this adjustment, the estimates should not be taken as definitive predictors of the potential effectiveness of bridge-to-bridge radiotelephone. The CAG assumes success in system implementation. When use of the system in a collision situation did not dictate otherwise, that assumption underlies the judgment of preventability. In addition, increasing traffic and increasing system use could compound the problems. On the other hand, improved training and procedures for bridge-to-bridge radiotelephone communication could work to increase the potential benefits of the system that are realized. Additional data for years following implementation of the regulation would strengthen the analysis of trends in system use and misuse that could be performed. The collision reports available for this analysis cover only through FY 1974.

FINDINGS

The effectiveness estimates are presented first. They are followed by presentation of other data related to collision potential during the period studied. Then a trend analysis is described, relating the bridge-to-bridge radiotelephone effectiveness data to the apparent pressures for increasing frequency of collisions. The trend analysis addresses the issue of the effects of system misues on its potential effectiveness. A summary of findings is then provided, followed by conclusions from the analysis. Finally, means of implementing the two possible, further regulatory initiatives concerning use of bridge-to-bridge radiotelephone are discussed.

Preventable Collisions

The data resulting from the CAG review are shown in Table 1. It includes, by year, the number of collision reports analyzed, the number of collisions determined to be preventable by Action 1 or Action 2, their total, and the ratio of the total to the number of collision reports in the sample for the year.

Figure 3 presents graphical information covering the full 11-year period. Fiscal year 1970 appears to be a turning point with the percentage of preventable collisions prior to 1970 falling between 38 and 59 percent (average 45 percent), while in the years following 1970, this value always falls between 16 and 25 percent (average 19 percent). The indication is that the general discussion preceding the passage of the Bridge-to-Bridge Radiotelephone Act in the early part of FY 1972 led to a general understanding of the value of the system and, consequently, an early implementation of its spirit well before the actual regulations were placed in force on 1 January 1973.

TABLE 1

RESULTS OF QEM BRIDGE-TO-BRIDGE RADIOTELEPHONE CASUALTY REPORT REVIEW

Fiscal Year	Number of Collisions[1]	Preventable By Action 1[2]	Preventable By Action 2[2]	Preventable By Action 1 Or Action 2	Percentage Preventable By Action 1 Or Action 2
1964	46	24	3	27	59 %
1965	30	11	2	13	43 %
1966	40	12	3	15	38 %
1967	41	11	5	16	39 %
1968	39	12	4	16	41 %
1969	44	14	7	21	48 %
1970	40	7	5	12	30 %
1971	36	4	2	6	17 %
1972	43	7	1	8	19 %
1973	40	8	2	10	25 %
1974	37	4	2	6	16 %

[1] The number of collisions shown comprises a 30 percent random sample of the collisions each year involving two or more ships or barge trains where the vessels involved are currently required by regulation to carry a bridge-to-bridge radiotelephone.

[2] Excludes all collisions in which bridge-to-bridge radiotelephone was used, even those determined to have been preventable, theoretically, on the basis of the other CAG criteria.

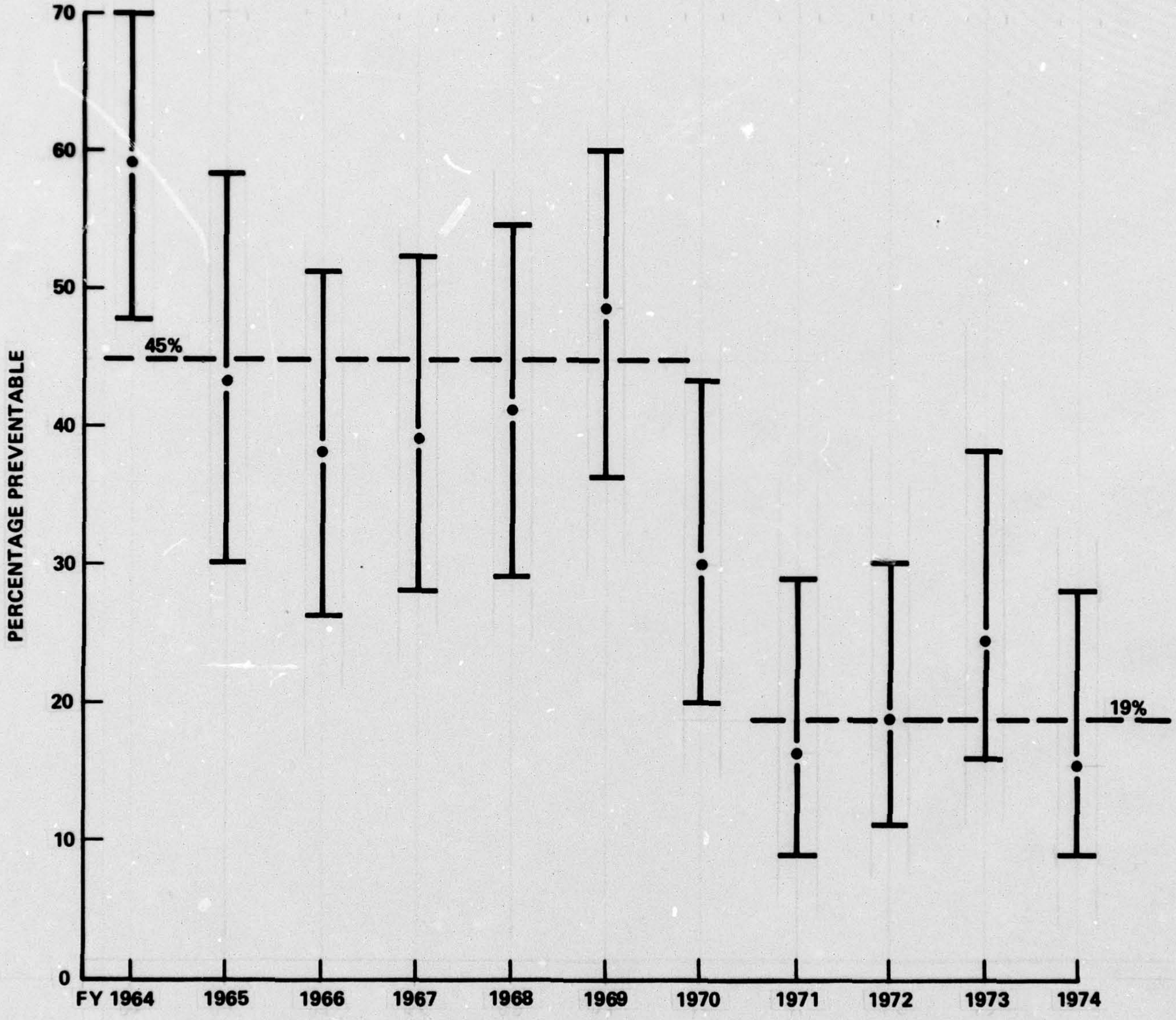

FIGURE 3. PERCENTAGES OF COLLISIONS POTENTIALLY PREVENTABLE BY BRIDGE-TO-BRIDGE RADIOTELEPHONE (95% Confidence Limits)

Figure 4 shows the cumulative percentage of casualties judged preventable by bridge-to-bridge radiotelephone for two periods before and after the apparent turning point in FY 1970. The figure illustrates increased assurance with which the results can be treated as the sample size increases. Assuming a binomial distribution of preventability outcomes, there is 99 percent assurance that the mean percentage of potentially preventable collisions was below 27 percent over the period 1971-1974.[5]

Impediments to Bridge-to-Bridge Radiotelephone Effectiveness

As previously indicated, the CAG review identified collisions judged to have been preventable by bridge-to-bridge radiotelephone, in which it was in fact used. Problems with its use were studied in the collision cause analysis (using the same 30% random sample employed in the bridge-to-bridge radiotelephone analysis) and were found to be categorized as follows:

- Not listening to proper frequency
- Too much voice traffic on channel 13
- Difficulties in establishing communications
- Misunderstanding what was said and misconstruing intentions and agreements
- Mistaking the identity of vessel with which an agreement was made by radiotelephone
- Not using bridge-to-bridge radiotelephones in situations in which it could have helped
- Agreeing to an infeasible passing.

Some of the above problems might be mitigated by training and regulation, but they are not likely to be eliminated. The extent to which use problems may reduce the potential anti-collision effectiveness of bridge-to-bridge radiotelephone must be considered, particularly in view of the fact that the total number of collisions during the years included in the analysis remained nearly constant. Data are provided in the next subsection which indicate that an increase in collisions might have been expected during the period and that, thus, the constant number represents an effective decrease in collisions as measured by a number of commonly used ratios. Following the discussion of number of collisions, further analysis is presented that supports the conclusion that bridge-to-bridge radiotelephone has indeed contributed to the effective decrease in collisions. Specifically, it is shown that we are not merely observing a paper transfer of collisions in which the rate of potentially preventable collisions appears to decrease because we have a new category of "nonpreventable" collisions in which the bridge-to-bridge radiotelephone is misused.

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[5] These confidence limits are tigher than those in the Phase II Report and the Interim Report because a more refined statistical model was used. (See Appendix E.)

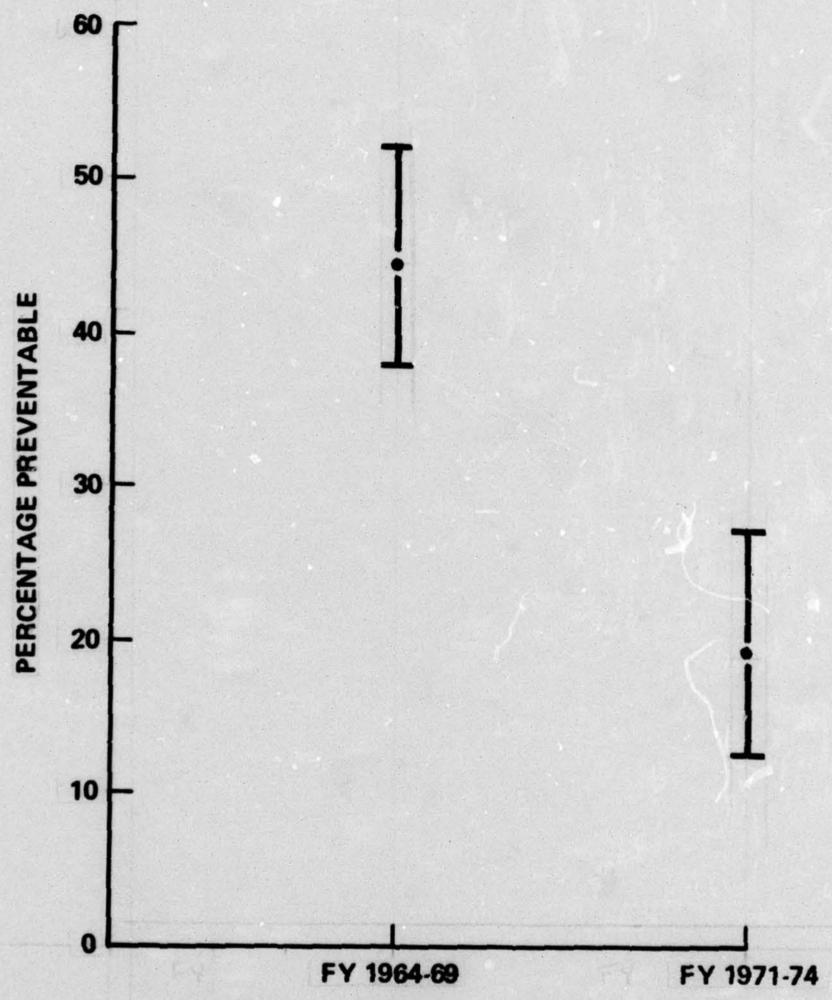

FIGURE 4. CUMULATIVE PERCENT OF COLLISIONS POTENTIALLY PREVENTABLE BY USE OF BRIDGE-TO-BRIDGE RADIOTELEPHONE (99% CONFIDENCE LIMITS)

Number of Collisions

While the study of preventable collisions above shows a decrease in the number of potentially preventable casualties through the use of the bridge-to-bridge radiotelephone, an explanation is needed for the absence of a like decline in number of collisions. Figure 5 graphs, on an annual basis, the number of collisions shown in Table 1, and also shows the total number of crossing, meeting, overtaking, and fog-related collisions from U.S. Coast Guard statistical summaries since FY 1964. The flattening of this curve since 1969 reinforces the steady rate shown in Table 1 figures. That this constant level is actually an effective decrease will be shown through an examination of the information contained in the following paragraphs.

Factors Influencing an Increase in Number of Collisions. An examination of other indicators influencing the number of collisions shows that all are either rising or at least steady. Table 2 indicates that an average of 86 percent of bridge-to-bridge radiotelephone preventable collisions involve tugs and barges and, of these, 84 percent occur in the Gulf Inland Waterway or Western River areas. These areas generally equate to the Gulf Intracoastal Waterway and Mississippi River systems used for the compilation of Department of Commerce and Army Corps of Engineers statistics. Department of Commerce data are shown in Figures 6 and 7. These data indicate that commercial tonnage in the Gulf Intracoastal Waterway and Mississippi River systems is rising at a rapid rate. Figure 6 shows that over the ten year period ending in 1972, cargo tonnage has increased by 84 percent above the level of 1963.

A factor which relates more closely to a measure of exposure to collisions is that of ton-miles of cargo shipped. These data are shown in Figure 7. The growth in ton-miles in the Mississippi River system over the period 1963-1972 is exactly 100 percent. Army Corps of Engineer statistics on numbers of trips shown in Figure 8 indicate this number is growing at a much slower rate than either tonnage or ton-miles figures. The indication is that the physical size and displacement of the average barge train and perhaps the length of individual voyages are increasing. Greater length and width of the average barge train will decrease its margin of maneuvering error within the confines of a fixed channel size. A greater average displacement tow for a given towboat results in less reserve power to maneuver the tow in dangerous situations. These indicators, while not as directly applicable as the statistics of the collision analysis, show that a reasonable expectation would be that the number of collisions should be increasing also.

Other factors which point toward an expected increase in the number of reported collisions are the recently instituted licensing regulations for towboat operators, more complete reporting of casualties, and the effects of economic inflation. The new licensing procedures will increase the awareness of towboat operators in regard to reporting requirements and will increase the incentive, through concern over possible license revocation, for better reporting. OCMI inspectors are now directed to examine deck and machinery logs on inspected vessels to ensure that all casualties are reported.[6] Economic infla-

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[6] USCG COMDT Inst. 59437, 3 April 1972, Marine Casualty Report: Improvements in obtaining.

TABLE 2

TUG AND BARGE COLLISIONS BY AREA

FY	Total	Collisions Involving Tugs and Barges[1]		GIWW[2]	Western Rivers[2]		Other Areas[2]	
1968	39	34	(87%)	19 (56%)	11	(32%)	4	(12%)
1969	44	38	(86%)	20 (53%)	8	(21%)	10	(26%)
1970	40	37	(93%)	26 (70%)	8	(22%)	3	(8%)
1971	36	31	(86%)	18 (58%)	7	(23%)	6	(19%)
1972	43	35	(81%)	20 (57%)	5	(14%)	10	(29%)
1973	40	34	(85%)	20 (59%)	10	(29%)	4	(12%)
1974	37	30	(81%)	17 (57%)	12	(40%)	1	(3%)

[1] Data from 30 percent random sample as described in note to Table 1.

[2] Percentage of tug and barge collisions in each area.

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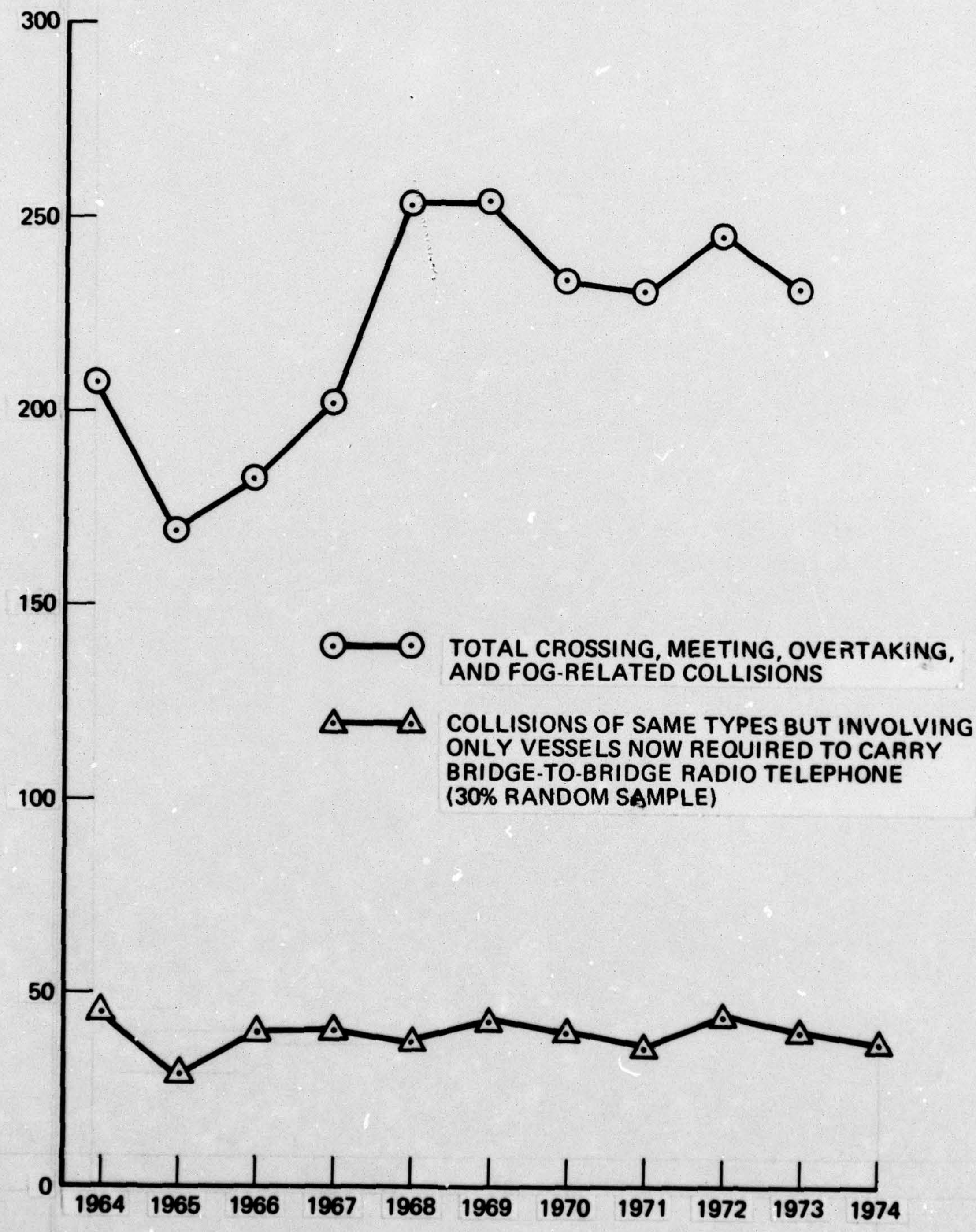

FIGURE 5. ANNUAL COLLISION STATISTICS

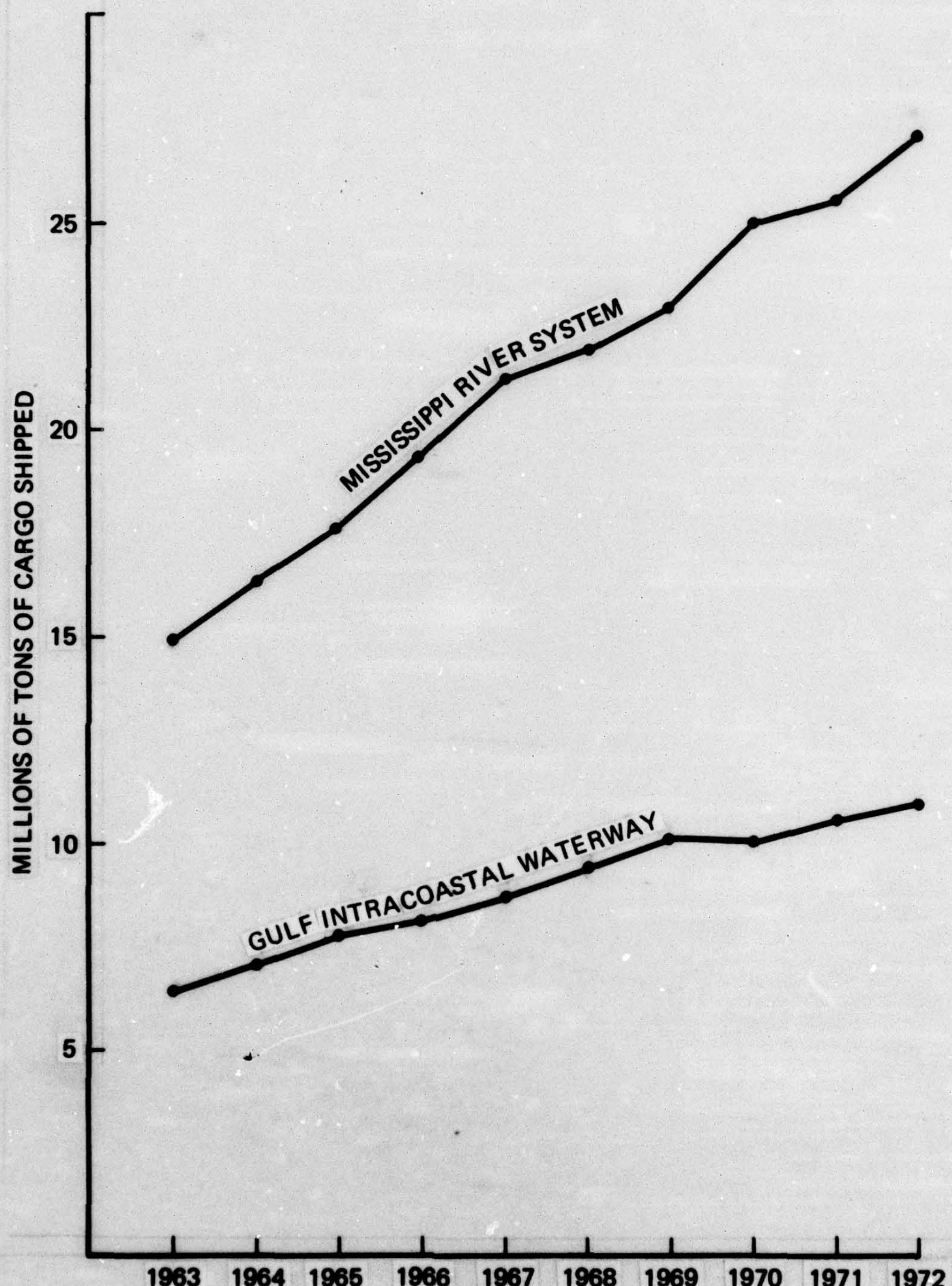

FIGURE 6. TONS OF CARGO SHIPPED ANNUALLY IN THE MISSISSIPPI RIVER SYSTEM AND GULF INTRACOASTAL WATERWAY

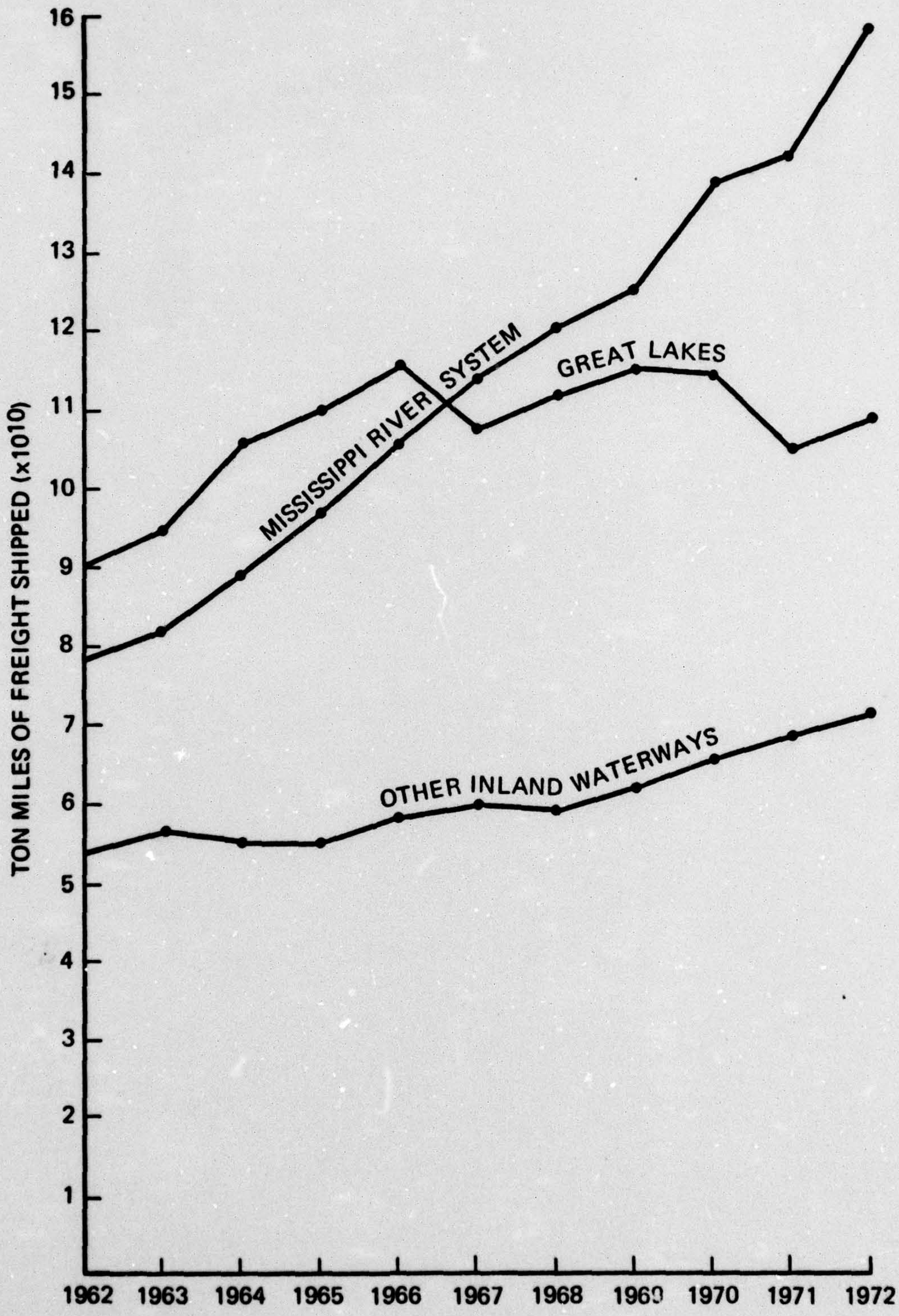

FIGURE 7. TON-MILES OF CARGO SHIPPED IN INLAND WATERWAY SYSTEMS

(69)

FIGURE 10 TUG OR TOWBOAT TRIPS (x100) IN THE GULF ~~OF~~ INTRACOASTAL WATERWAY AND MISSISSIPPI RIVER SYSTEMS

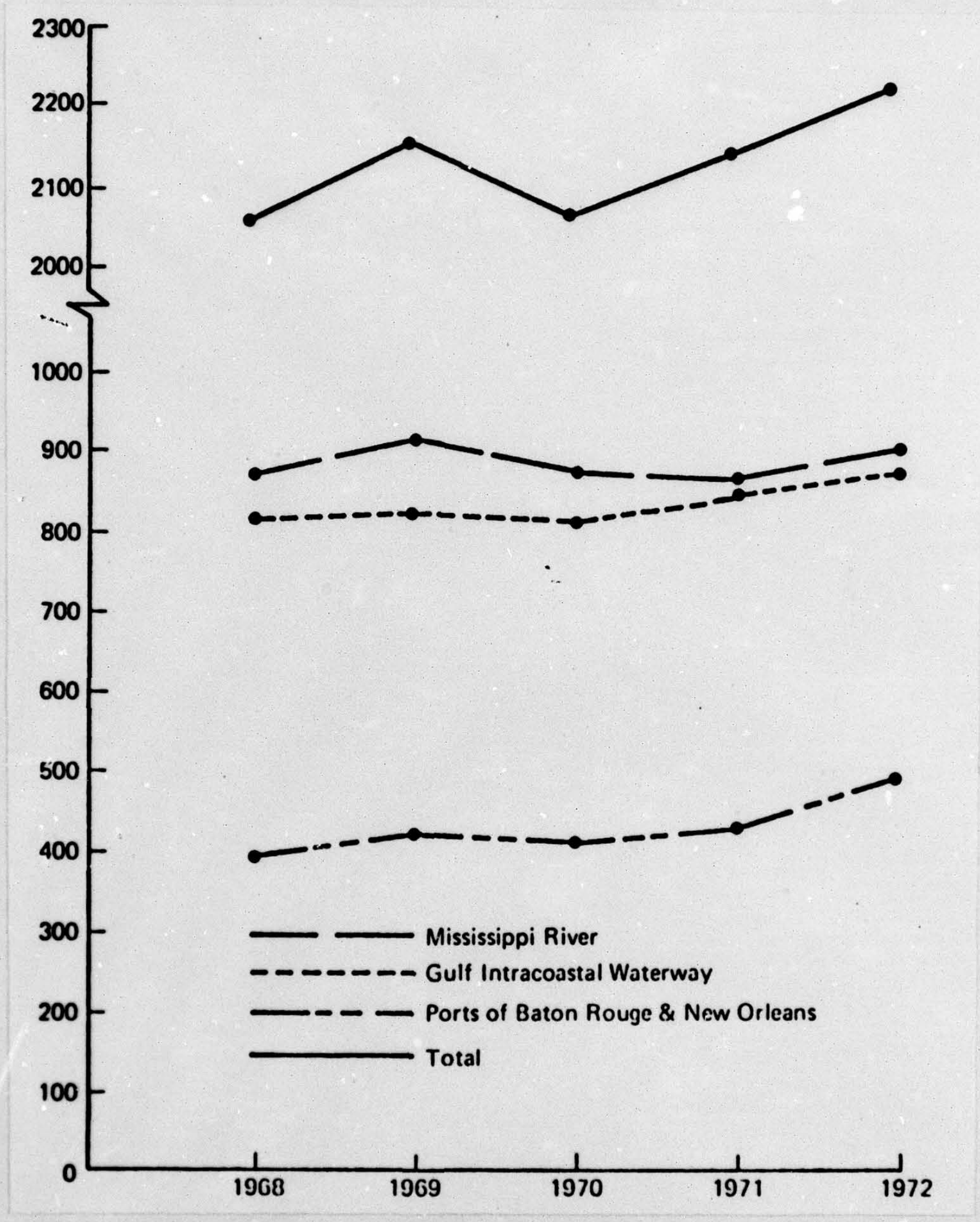

FIGURE 8. TUG OR TOWBOAT TRIPS (x 100) IN THE GULF INTRACOASTAL WATERWAY AND MISSISSIPPI RIVER SYSTEMS

tion leads to smaller casualties resulting in damages above the low limit threshold set by regulation.[7] A recent report covering the period 1969-1974 indicates that repair costs, estimated on the basis of the number of pounds of sheet steel required, have doubled. The estimator has risen from $.80 to $1.60 per pound. All of these factors are reflected in a significant increase in the number of casualty reports since 1972, as shown in Figure 9.

That the number of reported collisions is not rising in the face of all these factors which should be generating an increase, indicates that some additional force is acting to hold the number down. It appears that this can be attributed at least partially to collision reduction due to bridge-to-bridge radiotelephone. While the effect of other changes within the system may also be partially responsible, no one feature that could be examined as an alternative using the QEM has been uncovered.

It should not be inferred that there are no problems with the use of bridge-to-bridge radiotelephones; no system is faultless. As previously stated, collisions that are theoretically preventable by the use of bridge-to-bridge radiotelephone may occur when it is used. In some cases, problems in use of the system may result in not avoiding a potentially avoidable collision that originates from a sequence of conditions unrelated to the use of the bridge-to-bridge radiotelephone. At the extreme, misuse of the system could <u>create</u> unpreventable collision situations from situations that otherwise <u>might</u> have been benign. The casualty reports typically do not provide the kind of information necessary to make such a distinction. They do, however, provide enough information to consider the overall problem and to establish whether its proportions may be such as to degrade the usefulness of the findings of this analysis for evaluation of the regulations. The CAG review data provide some assurance on this issue, since collisions in which bridge-to-bridge radiotelephone was used were treated as unpreventable regardless of whether they otherwise exhibited the criteria of preventability. To explore the issue further, trend analysis was done, using the concepts of a special method of estimating casualty reduction potential developed earlier in this research.

Trend Analysis of Collisions When Bridge-to-Bridge Radiotelephone Was and Was Not Used

<u>Background</u>. Earlier in the Spill Risk Analysis Program, ORI formulated a method of estimating the casualty reduction potential which could be expected for a special class of system changes. That method is reflected in all aspects of the analysis of bridge-to-bridge radiotelephone effectiveness and in the other QEM analyses reported subsequently. The method is, however, demonstrated most explicitly in the trend analysis about to be described.

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[7] 46CFR136.05-1 requires reporting of vessel accidents resulting in over $1,500 damage as well as those resulting in any deaths or injuries which cause incapacitation over 72 hours. All groupings must be reported regardless of damage, injury, or death.

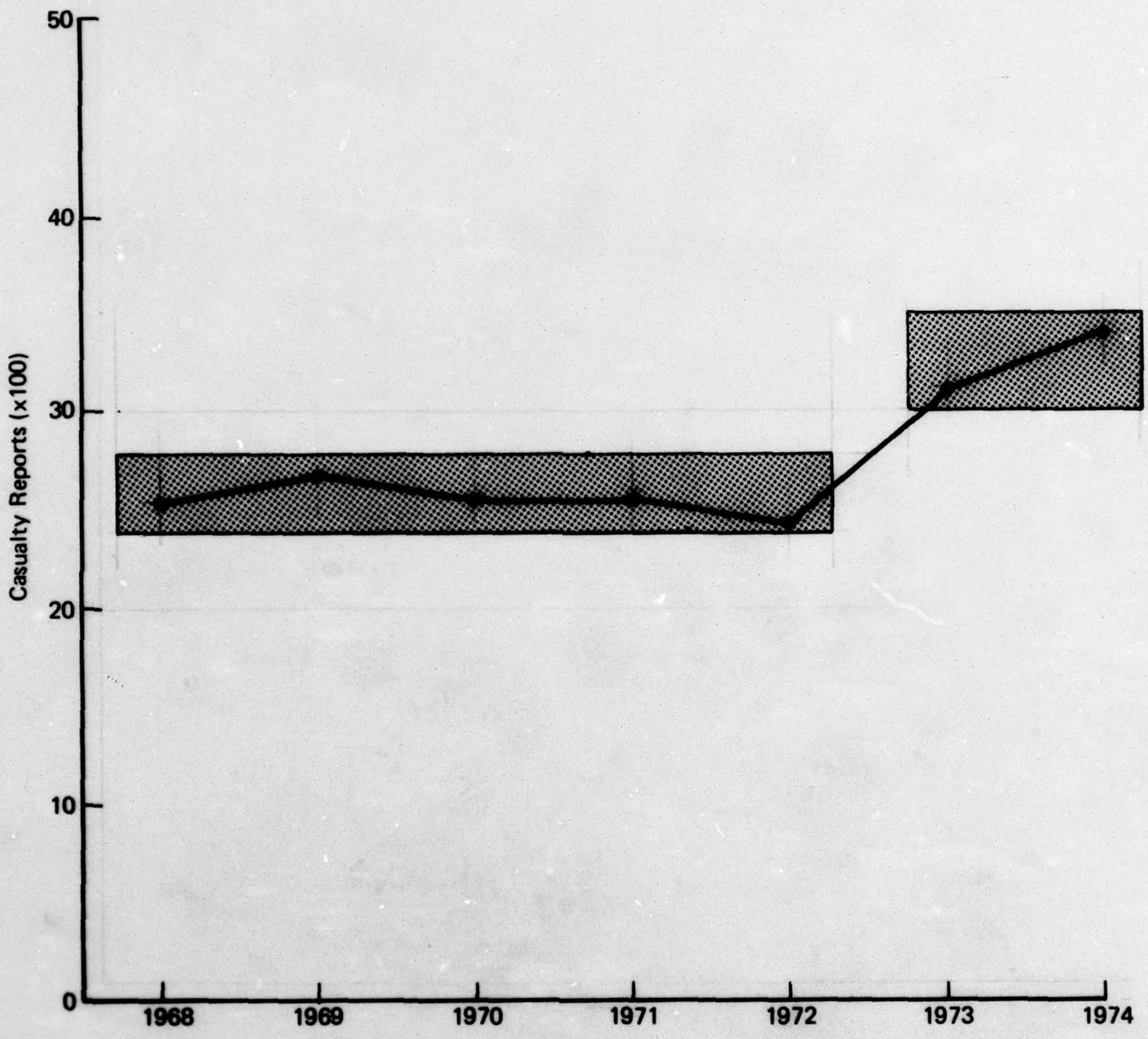

FIGURE 9. ANNUAL TOTAL CASUALTY REPORTS

(72)

Thus we incorporate here material from a previous report which sets forth the concepts involved.[8]

The method assumes that exposures to a type of casualty (e.g., collisions) may be categorized into two populations, E_1 and E_2, which are both exclusive and exhaustive. In the previous discussions such a categorization of exposures could have been the meetings in which both vessels actively utilized bridge-to-bridge radiotelephone and those in which they did not. Each exposure results in either a safe passing, State 1, or a casualty, State 2 or State 3. Finally, we assume the casualties which occur in conjunction with E_2 type of exposure can be characterized as those which probably would not have been prevented had the exposure been an E_1 type (State 2) and those which would (State 3).

A schematic of this situation is shown in Figure 10 where

E_i is the number of exposures of type i

r_{ij} is the branching ratio for exposure type i and the final state j which is given by N_{ij}/E_i

N_{ij} is the number of exposures of type i which reached the final state j.

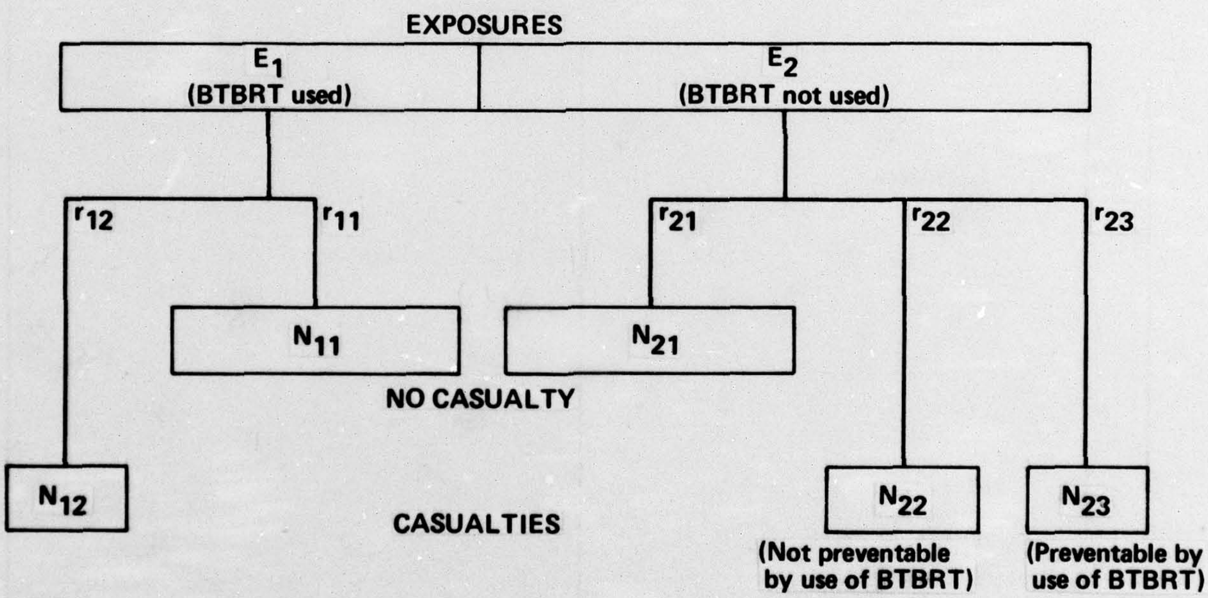

FIGURE 10. SCHEMATIC OF SYSTEM WITH TWO TYPES OF EXPOSURES
(Figure reprinted from earlier report; term definitions added.)

[8] ORI, Spill Risk Analysis Program, Phase II: Methodology Development and Demonstration, previously cited.

If we denote the total number of casualties which occurred during this time period as N_c, then we have

$$N_c = N_{12} + N_{22} + N_{23} = E_1 r_{12} + E_2(r_{22} + r_{23}).$$

A properly constructed Casualty Analysis Gauge will permit our allocating the casualties N_c to the appropriate N_{ij}. We now consider a system change which would eliminate the E_2 type of exposure but would leave the total number of exposures and the branching ratios unchanged. The changed system would then be depicted as in Figure 11 where

$$E_2' = 0$$

$$E' = E_1' = E_1 + E_2$$

$$r_{ij}' = r_{ij}$$

$$N_c' = N_{12}' = E_1' r_{12} = (E_1 + E_2) r_{12}.$$

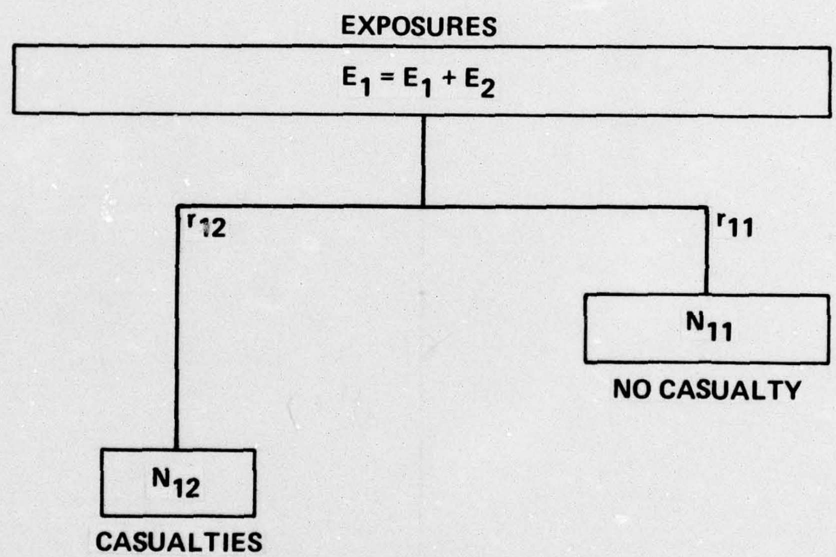

FIGURE 11. SCHEMATIC OF SYSTEM AFTER ELIMINATING ONE TYPE OF EXPOSURE (Figure reprinted from earlier report.)

Denoting ΔN_C as the number of casualties which could potentially be preventable by the envisioned system change we have

$$\Delta N_c = N_c - N_c' = E_2(r_{23} + r_{22} - r_{12})$$

$$= N_{23} + N_{22}\left(\frac{r_{22} - r_{12}}{r_{22}}\right) \quad (1)$$

Thus, we see that the envisioned system change would be expected to reduce the number of casualties by N_{23} plus a portion of the N_{22} casualties determined by the relative difference in the branching ratios r_{22} and r_{12}. In the preceding demonstrations of the improved use of bridge-to-bridge radiotelephone, we implicitly assumed that these branching ratios were approximately equal ($r_{22} \approx r_{12}$) and hence $\Delta N_C \approx N_{23}$. We justify this assumption on the basis of its reasonableness and also because the branching ratios themselves cannot be determined without estimates of the exposures ($r_{ij} = N_{ij}/E_i$) which are not generally obtainable. If, however, an estimate of the relative populations of the two exposure types (E_2/E_1) could be obtained, then Equation (1) could be evaluated in terms of obtainable data. To see this we simply note that the branching ratio term of Equation (1) may be written as

$$\frac{r_{22} - r_{12}}{r_{22}} = 1 - (E_2/E_1)\ (N_{12}/N_{22})$$

and have

$$\Delta N_c = N_{23} + N_{22} - (E_2/E_1)\ N_{12}. \quad (2)$$

We therefore see that if the ratio E_2/E_1 could be obtained, then an accurate estimate of ΔN_C would be determined from the number of casualties observed, N_{ij}, in the three categories.

Application of Method Concepts. Since there are no data for counting exposures, r_{ij} cannot be computed and the method cannot be demonstrated fully. However, we can count the number of collisions in which bridge-to-bridge radiotelephone was and was not used. We can also, by means of the CAG review, further partition those categories by the judgments of preventability/nonpreventability. Figure 12 is a revised version of Figure 10, reflecting the constraints of data availability. Figure 12 illustrates the logic by which the data were partitioned for this trend analysis. Note that collisions judged to have been preventable by the use of bridge-to-bridge radiotelephone, but in which it was used, are treated as a separate category, N13, of nonpreventable collisions.

Referring to Figure 12, we have no data which will allow us to count N11 and N21. On the other hand, we can count N12, N13, N22, and N23, for each of the 11 years reviewed. Knowing that the total of these four factors has remained relatively constant over the period, and that N23 has decreased, it is apparent that the sum of N12, N13, and N22 has increased. We want to know whether this increase is the result of a simple transfer from N23 to N13. That is, are all of those collisions which would be potentially preventable if bridge-to-bridge radiotelephone were used still occurring when it is used?

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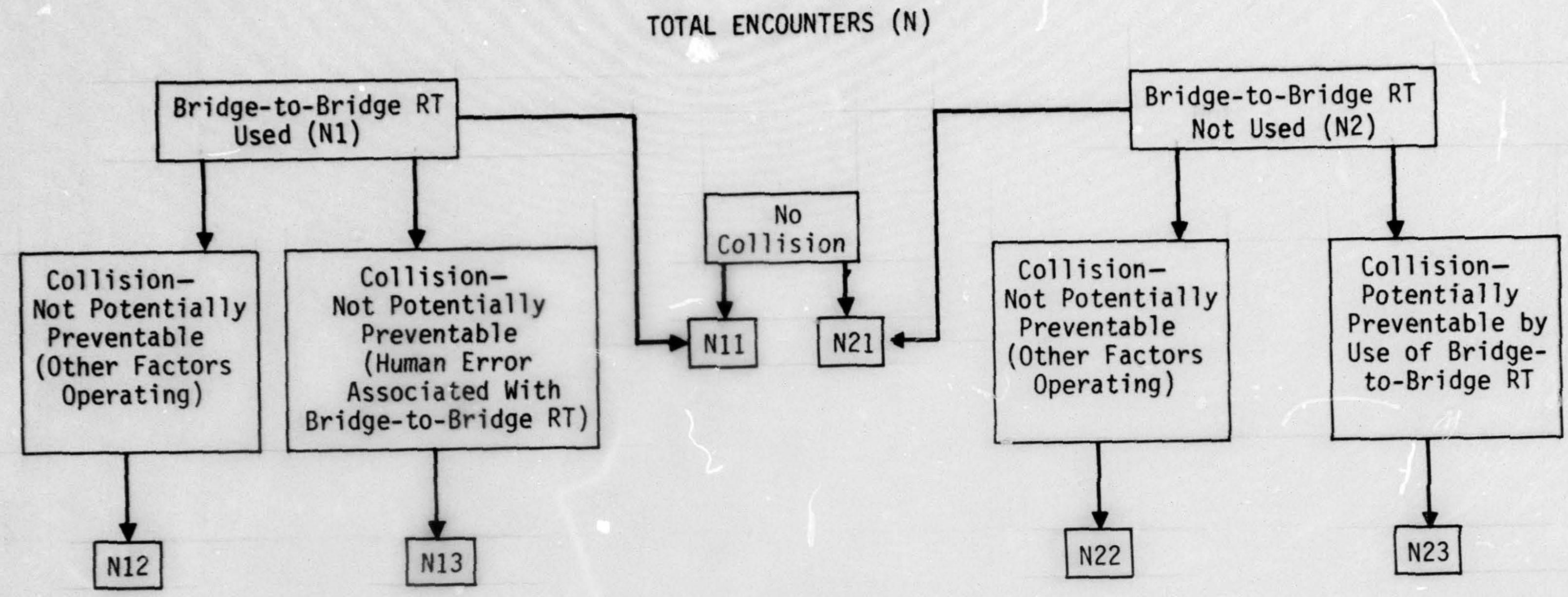

FIGURE 12. LOGIC DIAGRAM ASSOCIATED WITH BRIDGE-TO-BRIDGE RADIOTELEPHONE USE

(76)

Table 3 shows the data from the CAG review partitioned according to the collision categories shown in Figure 12. The results of the least-squares analysis of the Table 3 data are illustrated in Figure 13. The rate of decrease in N23 clearly exceeds the rate of increase in N13, as reflected in the slopes of the least-squares lines. Thus misuse or problems in use of the bridge-to-bridge radiotelephone were not negating the potential benefits of the system. We may infer that N11 also increased over the 11-year period. That is, we may infer that use of bridge-to-bridge radiotelephone did contribute to holding the number of accidents relatively constant over the period.

This conclusion is further supported by the least-squares trends of collisions judged not preventable by the use of bridge-to-bridge radiotelephone. N12 increases while N22 decreases only minimally. (It is evident that vessel personnel discriminate as to when bridge-to-bridge communication may be helpful to avoid a collision; a complete transfer from N22 to N12 would not be expected.) Thus, the frequency of encounters raising the possibility of a collision not preventable by use of bridge-to-bridge radiotelephone had to increase. There is no reason to believe that the ratio of encounters raising the possibility of those two categories of collisions changed during the years studied. (That is, we continue to assume a binomial distribution of encounters classified as preventable/not preventable by the use of bridge-to-bridge radiotelephone.) If encounters associated with the "not preventable" category increased, it must be assumed that encounters associated with the "preventable" category increased proportionally. Therefore, the frequency of collisions preventable by the use of bridge-to-bridge radiotelephone decreased, despite increasing opportunity, which result can only be attributed to system effectiveness.

SUMMARY OF FINDINGS

The percentage of collisions potentially preventable by the use of bridge-to-bridge radiotelephone since 1970 is less than one-half as large as the same percentage was during the 6 years prior to 1970.

The number of collisions reported has remained relatively constant over the period 1968-1974, and has ceased the climb observed in earlier years.

All applicable collision exposure statistics tend to indicate that the number of reported collisions should be rising, unless effective safety improvements were coming into play.

CONCLUSION

The increased capacity for collision avoidance generated through the use of bridge-to-bridge radiotelephone has resulted in an effective decrease in the number of ship collisions by holding this number constant in the face of a large number of upward pressures.

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TABLE 3

CAG REVIEW DATA CHARACTERIZED BY TYPE OF COLLISION

Fiscal Year	N12	N13	N22	N23	Total
1964	6	2	11	27	46
1965	0	3	14	13	30
1966	5	1	19	15	40
1967	9	2	14	16	41
1968	5	5	13	16	39
1969	7	7	9	21	44
1970	7	5	16	12	40
1971	6	8	16	6	36
1972	5	6	24	8	43
1973	13	14	3	10	40
1974	12	7	12	6	37

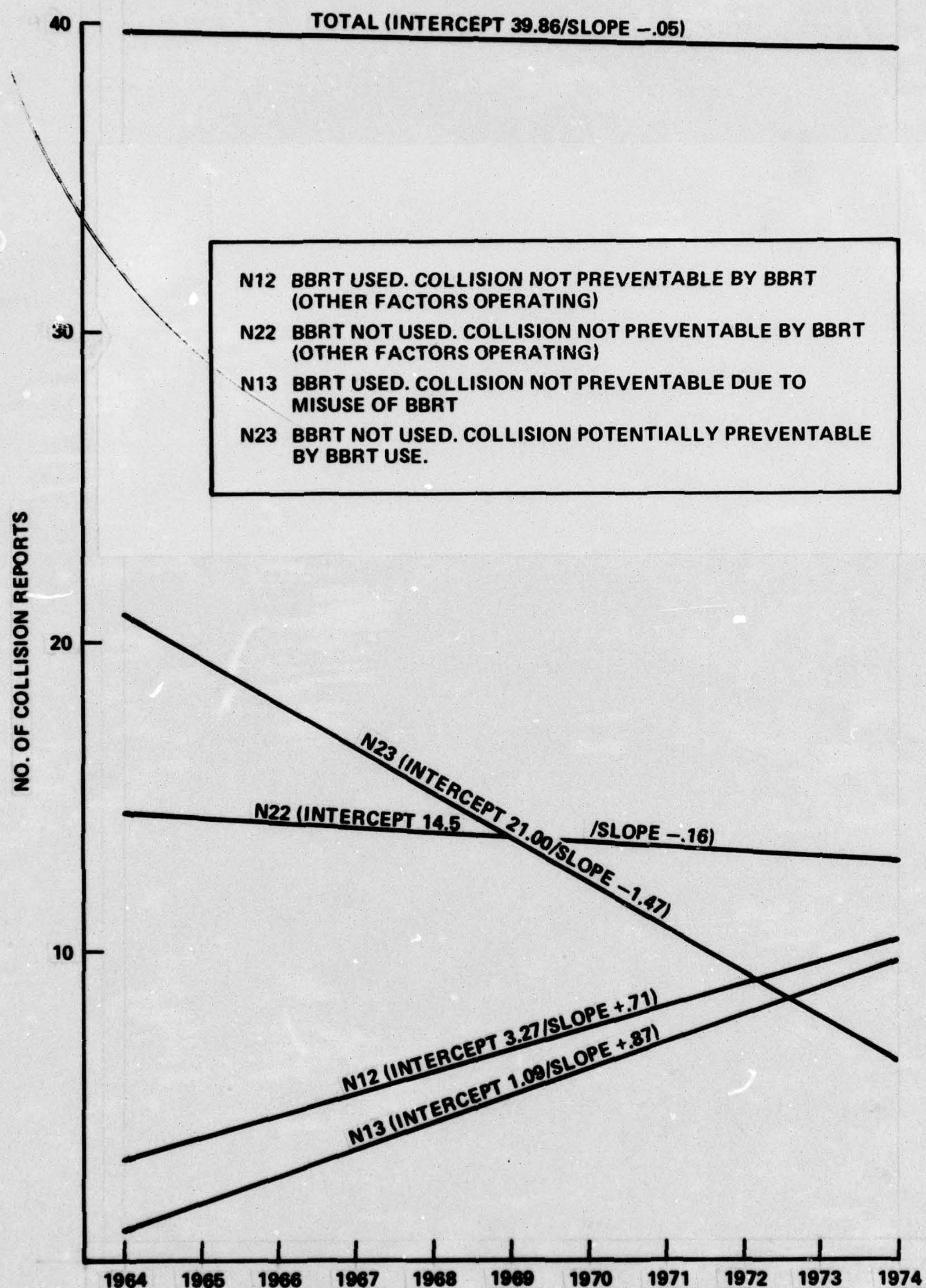

FIGURE 13. LEAST-SQUARES TRENDS OF QEM DATA

RECOMMENDATIONS FOR IMPLEMENTATION OF POTENTIAL COAST GUARD ACTIONS 1 AND 2

The above results estimate the potential effectiveness of the two actions in reducing casualties and spills. In one sense these estimates are conservative since the gauges and method used to estimate whether or not a given casualty could have been prevented resolved all reasonable doubt (or disagreement) against the casualty being prevented by the action. In another sense, the estimates are generous since they assume the actions can be implemented to a high degree. In any case, measures designed to implement the actions will only approach the potential casualty and spill reductions providing there are no serious operational difficulties in implementing the actions.

Implementing Action 1—Use of Bridge-to-Bridge Radiotelephone to Achieve Passing Agreement

Detailed analysis of the casualty reports, and a study of human factors involved, suggest the following means of implementing the first action:

- Require that bridge-to-bridge radiotelephone (rather than whistles) be designated as the primary means of communicating and obtaining passing agreements.

Discussion and interviews with persons involved with ship operations (pilots, masters, mates and owner company officials) have revealed that they would not have a strong prejudice against the above suggested requirement providing it would replace the existing whistle requirement. There was, however, some concern expressed by several of the above persons that an overloading of channel 13 might possibly result in a few high traffic density locations and that this possible overloading might cause additional confusion in some passing situations.[9] While this possibility should not be ignored, it seems unlikely that the extensive use of the bridge-to-bridge radiotelephone to communicate passing agreements would ever result in a net degradation in marine safety.

Although the necessary equipment and basic skills are already present, it will not be an easy matter to change the long-standing habits of many of the present operating opersonnel. We believe that effective means of educating users of the need for the change, and the benefits to be derived therefrom, will greatly assist in implementing this remedy. Thus, in addition to changing the primary method of communicating passing agreements, way to promote the benefits of this change must be considered. A possible approach would be to publish (in Proceedings of the Merchant Marine Safety Council) examples of collisions which could have been prevented by the proper use of bridge-to-bridge radiotelephone.

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[9] Section 2 of the Act refers to "frequency or frequencies dedicated to the exchange of navigational information." Thus the option of additional channels is open.

Implementing Action 2—Use of Bridge-to-Bridge Radiotelephone For Security Calls

Detailed analysis of the casualty reports, and a study of the human factors involved, suggest the following means of implementing this action.

- Require that bridge-to-bridge radiotelephone (rather than whistles) be made the primary means of making security calls when approaching blind bends or bridges.

We note that bends and bridges are almost exclusively a feature of inland rivers and canals which are heavily travelled by barge traffic. The bends and bridges also frequently constitute situations of severely reduced maneuvering room. In many of these situations, it appears that a safe passing of two barge trains would be most unlikely, if not actually impossible. For this reason, every effort must be made to avoid a meeting situation in such locations. From numerous discussions with both Coast Guard and barge operating personnel, it appears that this problem is well understood by operating personnel. Unlike the straight channel passing situation, the bridge-to-bridge radiotelephone is extensively used on rivers and canals to make security calls and thereby avoid meetings (and probable collisions) at blind bends and bridges. This factor probably leads to the considerably lower number of collisions preventable by Action 2, shown in Table 1. It is therefore thought that the educational campaign mentioned in conjunction with the implementation of the first action is not as critical to the successful implementation of this action.

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COLLISION AVOIDANCE RADAR SYSTEM EFFECTIVENESS

INTRODUCTION

In this analysis, the objective is the evaluation of the predicted effect of a proposed regulation. The regulation in question would require that all U.S. and foreign vessels of more than 10,000 gross tons in U.S. waters and bound for or departing from U.S. ports mount two radars. One radar would be equipped with an "anti-collision" device. This regulation was proposed and published for comment by interested persons in the Federal Register, Volume 39, Number 126, Part IV, dated June 28, 1974. The characteristics of a Maritime Administration Collision Avoidance System which would qualify new construction vessels for federal subsidies are detailed in Appendix F. The problem facing the Coast Guard is whether or not a collision avoidance system is likely to have an appreciable effect in reducing ship collisions.

A contributing cause in many collisions is that threats are not properly perceived and, therefore, early action at collision avoidance is not taken. The Collision Avoidance Radar System would provide for automatic tracking of targets to determine whether each target is a potential collision threat. The system would warn watchstanders by means of an audiovisual alarm when the predicted closest point of approach (CPA) of another vessel results in a dangerous situation. The detection <u>and</u> evaluation function then would not be susceptible to lapses in attention or human error. The system, of course, is not foolproof and, as with any man-machine system, there is always concern about which tasks are better performed by the machine and which by the man. The radar is fallible because detection is not always possible when sea return, an obstructing land mass, vessel, or man-made object, small boat, or heavy rain hinder its normal detection capability. Also, collision avoidance systems cannot accurately predict a CPA when a target is frequently changing course. The projections of its path and calculations of CPA and time to CPA (TCPA) are based upon a present estimated course and speed. If two vessels are each following the irregular course of a channel or river and, additionally

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if they must by necessity pass close to one another, the collision avoidance system may prove of little value other than as an aid in initial detection.

In the context of detection and evaluation, let us now consider the human operator. Human perception may at times be inadequate. When fatigue is a factor or when multiple tasks and duties must be carried out, a proper lookout may not exist at the crucial period during which another vessel comes into close range. Further, even if the watchstander knows of the presence of another vessel, he may not accurately estimate the range, course and speed of that vessel. He may misjudge a crossing situation to be a meeting scenario and inadvertently violate his duty as the privileged or burdened vessel with either an inappropriate maneuver or a failure to yield the right of way. When it is functioning properly and when the other vessel is not making frequent maneuvers, a Collision Avoidance Radar System offers a clear and accurate presentation of the course of the other vessel and the possibility of determining ahead of time the consequence of a maneuver. When the ship is a very large one, the latter feature may be important, since very early action is required to affect the course and speed of a large vessel. A change of mind at a later time may not be feasible. Along the coast and on the open ocean, a Collision Avoidance Radar System would seem to have significant value. However, it must be recognized that there are many cases in which the automated radar system will not accurately predict a CPA and the operator must use his experience to determine the existence of a threat. With a turning ship in a channel or harbor perhaps the best information a master or pilot needs may be his knowledge of the channel, along with experienced judgment about the most probable course a ship may take based on past experience and familiarity with the local currents, channel characteristics and local pilotage practice. Using the Quasi-Experimental Method, it is possible to examine past collisions and the circumstances surrounding them, and to draw conclusions about how frequently the system might have been helpful in collision avoidance.

PREVENTABLE COLLISIONS—WHEN WOULD THE COLLISION AVOIDANCE RADAR SYSTEM HELP?

For this study, 198 collisions of two underway vessels in which at least one was 10,000 gross tons or larger were reviewed. This number constitutes all such collisions reported to the Coast Guard during Fiscal Years 1970-1974. A Casualty Analysis Gauge was constructed so that the possibility of prevention of each collision could be decided. With the above discussion as a base on which to develop the criteria for possible preventability, a list of questions was drawn up similar to the one in the previous section on bridge-to-bridge radiotelephone. However, more complicating factors had to be taken into account to determine preventability in the collision avoidance system analysis. The first criterion was lack of proper detection/evaluation of the target threat by the ship(s) meeting the size requirement for our study. Second, ship personnel must have acted as prudent men would have been expected to act under the circumstances. Third, basic radar functioning must not have been impaired either by a malfunction, by an obstructing land mass, vessel, or other objects, by sea return, or by heavy rain. Fourth, the target vessels must not have made maneuvers following detection which would have rendered CPA predictions inaccurate.

Even after meeting all of the above criteria, there were a few cases where a reader determined that the collision would not be preventable because a radar operator who had information about threats did not communicate this to the conning officer. Also, if the collision occurred in a straight channel, there is some question about the utility of a Collision Avoidance Radar System, since a close meeting may be forced and, naturally, the CPA is expected to be small. Finally, the accuracy and resolution of the radar may not yield the necessary precision regarding the other vessel's position in the channel.

THE CASUALTY ANALYSIS GAUGE FOR THE COLLISION AVOIDANCE RADAR SYSTEM

Using the criteria above, a casualty analysis gauge was developed similar to the bridge-to-bridge radiotelephone gauge. A series of questions was posed to a reader of collision cases, enabling him to classify the case as one which is possibly preventable or not preventable. Figure 14 illustrates the logic of the gauge and the actual list of questions may be found at the beginning of Appendix B.

This gauge was applied at the same time the collision cause gauge was applied. It was found that approximately 15 to 20 minutes was spent evaluating each case. Some of the more simple letters-of-transmittal cases required only 5 to 10 minutes, with some of the more complex narrative cases sometimes needing as much as 30 minutes. These time estimates apply for the Collision Avoidance Radar System gauge alone. The collision cause analysis required additional time. The answers were recorded on large sheets, the results by each reader compared, conflicts in answers resolved, and the final result transferred to forms which are reproduced in Appendix B.

RESULTS OF THE QUASI-EXPERIMENT FOR THE COLLISION AVOIDANCE SYSTEM

The basic finding of our analysis was that the criteria for possible preventability were present in only 9.6 to 13.1 percent of the cases reviewed.

In only 32% of the cases was a lack of proper detection and evaluation about the collision threat by a large ship found to be a contributing factor in the collision. Out of this smaller set, 30% were considered to be preventable with the Collision Avoidance Radar System. In 3.5% of the cases (7 cases) there was either (1) a disagreement between the readers about the preventability (5 cases) or (2) both readers were not willing to classify the case as possibly preventable or definitely not preventable (2 cases). Table 4 summarizes the complete breakout of CAG findings. Table 5 provides a year by year account.

Table 6 shows an assessment of which basic component of the Collision Avoidance Radar System would be the one aiding in the 19 cases designated as possibly preventable. In 12 of these cases (63%) the audiovisual alarm would have helped by alerting the watchstander of impending collision. In 13 cases (68%) the CPA/TCPA/Target Priority function would have provided useful information about the scenarios and most likely would have led to a different course of action. In just 3 cases (15%) the simulated maneuver would have

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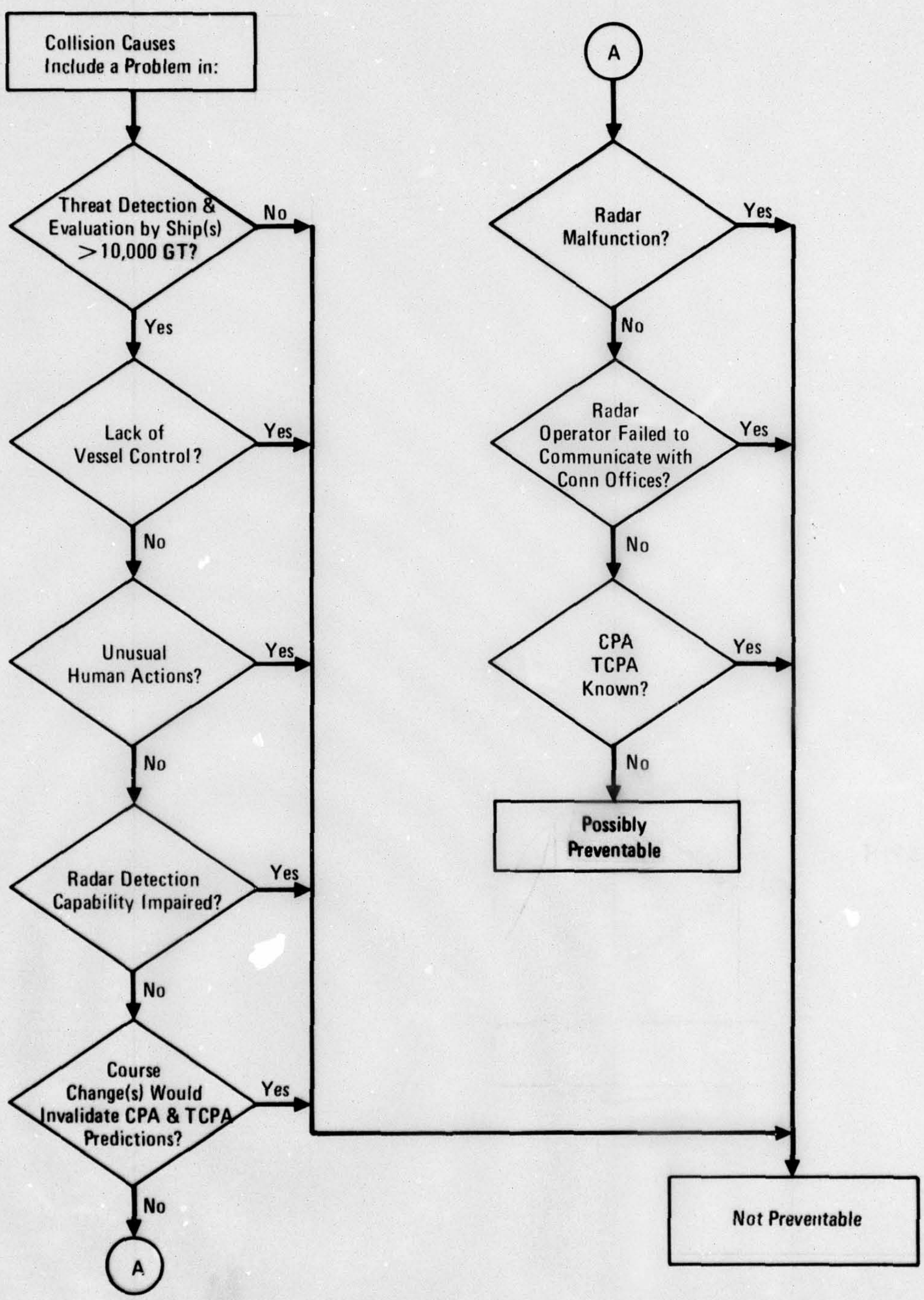

FIGURE 14. COLLISION AVOIDANCE RADAR SYSTEM CASUALTY ANALYSIS GAUGE LOGIC DIAGRAM

TABLE 4

BREAKDOWN OF SELECTED COLLISION CASES (FY 1970-74)
FROM CARS QUASI-EXPERIMENTAL ANALYSIS

	Number of Cases	Percentage of Total
1. Total number of collision cases	198	100.0
2. Cases in which detection/evaluation of threat was a deficiency in ship(s) greater than 10,000 gross tons	63	31.8
3. Preventable by CARS	19	9.6
4. Cases as above (2) less those which are preventable (3)	44	22.2
5. Cases in which there was a disagreement between readers as to preventability	5	2.5
(4) minus (5)	39	19.7
6. Cases in which both readers were uncertain about collision being preventable	2	1.0
7. Cases in which detection/evaluation deficiency by ship(s) greater than 10,000 gross tons and was determined to be not preventable	37	18.7

(87)

TABLE 5

COLLISION AVOIDANCE RADAR SYSTEM ANALYSIS RESULTS
FOR EACH YEAR, FY 1970-1974

	1970	1971	1972	1973	1974
Number of collisions	35	36	43	48	36
1. Detection/evaluation of threat deficiency (Question 1 = Y)	9	13	8	18	15
2. Preventable collisions (Question 16 = P)	5	2	0	7	5
3. Disagreements (Question 16 = P/NP)	0	1	3	0	1
4. Uncertain (Question 16 = ?)	0	0	0	2	0
5. Question 1 = Y and Question 16 = NP; (5) = (1) - (2) - (3) - (4)	4	10	5	9	9

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TABLE 6

COLLISION AVOIDANCE RADAR SYSTEM COMPONENTS: NUMBER OF CASES EACH YEAR WHERE EACH MIGHT HAVE AIDED IN COLLISION PREVENTION

Component	1970	1971	1972	1973	1974	Total
Audiovisual Alarm	4	2	1	3	2	12
CPA/TCPA/Target Priority	4	1	2	3	3	13
Simulated Maneuver	1	0	0	2	0	3
Transponder Information (not including intention data)*	0	0	0	0	0	0

*Note: The transponder component is not included in the description of the MARAD system presented in Appendix [illegible].

been helpful, and in no case was further information like that obtainable through a transponder system thought to have significant utility.[1]

Table 7 is a detailed account of line (7) in Table 4. In those cases, where proper threat detection and evaluation was not made and the collision was judged not preventable by a collision avoidance system, the reason was often found in external circumstances which impaired the radar's detection capability (an obstructing land mass, bridge, rain, sea return, etc.), or the other vessel was engaged in maneuvering which would invalidate accurate predictions of the target's future location based on a simple linear projection of current course and no speed change.

COLLISION CASUALTY REPORTS

In considering the conclusions of this study it may be of interest to know something about the data source which was used. First, casualty case reports are filed at Coast Guard Headquarters by the casualty review branch (G-MVI-3). The criteria for selecting the cases to be studied were:

1. The collision was between two underway vessels.

2. At least one of the vessels was over 10,000 gross tons.

3. The scenario was a meeting, overtaking, or crossing situation, or occurred in fog. (Fog takes priority over the other three categories.)

Every collision during the FY 1970-1974 period meeting these requirements was selected and xeroxed for use in this study.

Naturally, our conclusions are only as good as the information on the Report of Vessel Casualty or Accident forms (CG2692), and either the letter of transmittal or the narrative description of the casualty, which constitute these files. For the most part sufficient information was found in the reports to facilitate the analysis. However, there were some reports which were missing vital information about the casualty. Fuller descriptions are a part of the permanent files of the individual Coast Guard districts and portions were apparently retained when the case was forwarded to the headquarters in Washington, D.C. It should be noted that some of the information which was collected from the case reports is also contained in the computerized data base at Coast Guard Headquarters. For this study, all questions in each gauge were answered directly from the copy of the casualty report to ensure the objectivity of the QEM, based on two readings by separate reviewers.

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[1] Although we make this statement about transponders, this was not the primary focus of our study and, hence, should not discourage a closer look at such equipment and its usefulness. In particular, the inclusion of intended maneuver information was not considered.

TABLE 7

FACTORS WHICH LED TO COLLISION BEING NOT PREVENTABLE WITH COLLISION AVOIDANCE RADAR SYSTEM FOR THE 37 CASES WHERE THREAT DETECTION/EVALUATION DEFICIENCY WAS A PROBLEM IN A SHIP OF GREATER THAN 10,000 GROSS TONS AND BOTH READERS AGREED CASE WAS NOT PREVENTABLE

Factor Indicating Non-Preventability	Number of Cases	Percentage of 37
Lack of vessel control	3	8.1
Unusual human action	4	10.8
Radar detection capability hampered	16	43.2
Maneuver(s) precluded course projection and CPA prediction	18	48.6
Radar system malfunction	2	5.4
Radar operator did not communicate with Conn Officer	1	2.7
Total	44	118.9

Note: In seven cases (18.9 percent) two factors were acting together.

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PAST DATA vs. THE FUTURE

A consideration to briefly touch upon is whether the analysis of 5 years (FY 1970-1974) tells us anything about the future. One way to find out is by examining the data for time trends which might continue into the future. The data for the 5-year period indicates that there were more collisions each year up until 1974. The rate of increase in the years 1972 and 1973 was approximately 14% per year over the levels for 1970 and 1971. The number and percentage of cases estimated as preventable slightly increased over the years, but only by 4.4%, from a mean of 9.9% for FY 1970 and 1971, to a mean 14.3% for FY 1973-1974. These percentages are higher than the overall 9.6 figure stated earlier, due to the fact that no cases in FY 1972 were found to be preventable. The total number of cases in 1974 violated the trend of the previous 4 years. This may be due in part because not all of the cases for FY 1974 were in Coast Guard Headquarters files four months after the close of the fiscal year when the cases were retrieved. It is quite natural for this to happen since some of the investigations require more time than others to reach completion and be closed. However, it seems very unlikely that this would account for the entire 25% drop in the number of collisions from 1973 to 1974. Additional factors, including random fluctuation, may have been acting. A least-squares analysis of the trend indicates a mean increase of 3.9% per year as shown in Figure 15.

Besides analyzing the trend data, however, one may think about how the system works and the trend of growing traffic on the oceans and in harbors and waterways, and attempt to make some conjectures. While a Collision Avoidance Radar System would help in some cases to sort out confusion, the greatest burden most likely is going to fall upon the seamen—to be attentive, competent, and cautious. While more information of the kind provided by a collision avoidance system would be useful, there would also be more cases in which such information would not be of significant help. Most of the congestion from an increase in traffic will show up in the ports and restricted waterways of the world, since the number of these ports and waterways is relatively fixed. On the other hand, ocean traffic does not face geographic restrictions. More traffic does not necessarily mean more dangerous encounters. That is, it would be relatively easy to establish navigation lanes with passing distances sufficient to minimize, if not eliminate, the danger of collision. Arguing from the conservative position that accidents happening in ports and waterways will remain at about the same percentage, the small fraction of collisions possibly preventable with a collision avoidance system should stay at about the same level. However, taking the more realistic view that there will be some increases in marine traffic, results in a prediction that a smaller fraction would be possibly preventable for the reasons cited earlier (concerning problems in using a collision avoidance system in close maneuvering situations). Navigation lanes and traffic monitoring with shore-based radar VTS (Vessel Traffic Systems) should be consequently more useful. Therefore, outside trend information generated from this analysis does not seem to indicate a significant likelihood that Collision Avoidance Radar Systems of the type described in Appendix F are going to be more effective in the future in preventing collisions than they are today.

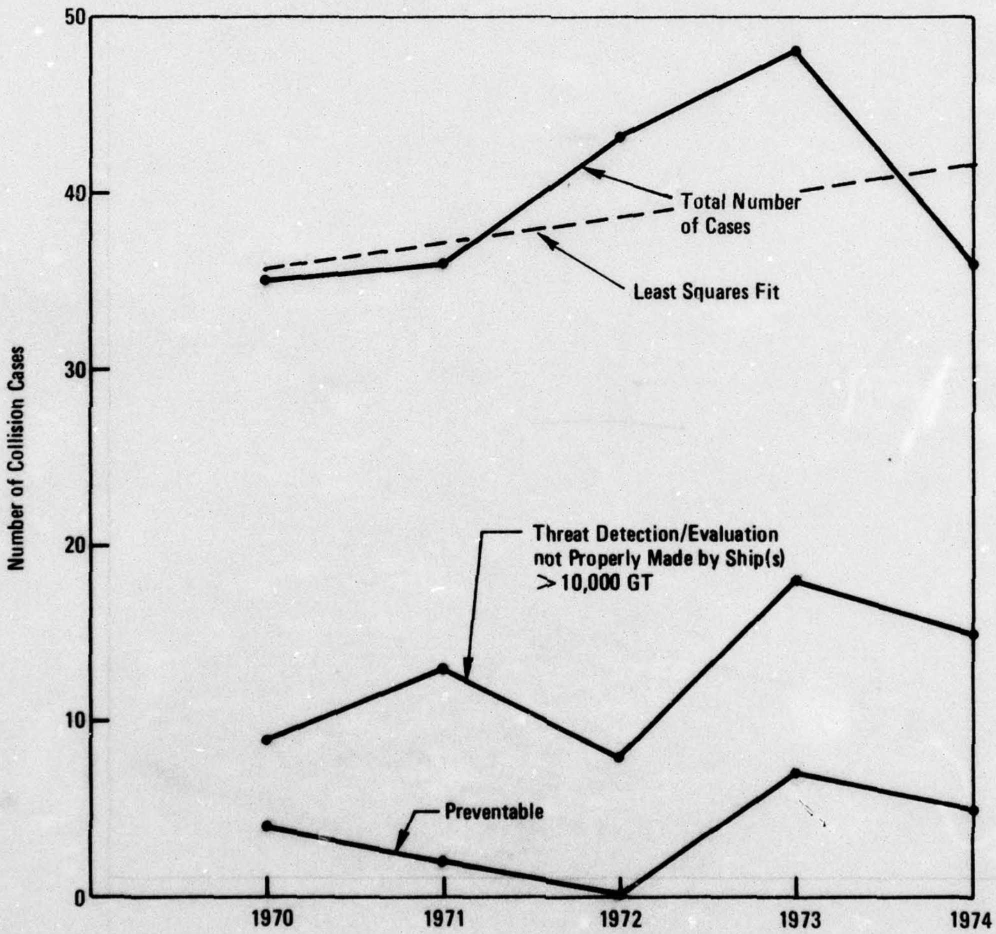

FIGURE 15. COLLISION AVOIDANCE SYSTEM ANALYSIS MAJOR RESULTS

(93)

On the other hand, if attention and effort are put into the collision problem on other fronts, it may well be that the type of collisions judged not preventable in this study could be greatly reduced, thus making shipboard collision avoidance systems more significant in terms of the entire population of collisions with large ships.

SUMMARY

The major conclusion of this analysis is that the criteria for possible preventability of collisions by collision avoidance radar were present in only 9.6 to 13.1 percent of the cases. The range results from disagreement or uncertainty of the analysts concerning 2.5 percent of the cases. This range represents the theoretical maximum collision prevention capability of a 100% effective system. Anything less than perfect reliability, perfect interface with the operator and perfect performance by the operator of tasks related to system use would degrade maximum collision prevention capability. No definitive estimate of the practical maximum effectiveness of Collision Avoidance Radar Systems was feasible within this study. Hence, the best we can say is that no more than 13.1 percent of the 198 collisions during the FY 1970-1974 period between two underway vessels where at least one was larger than 10,000 gross tons *might possibly* have been prevented.

A second finding is that in 68 percent of the collisions, a lack of proper detection and evaluation of the collision threat by the 10,000 gross tons or larger ships was not a contributing cause of collision. In other words, collisions between large ships are not frequent events relative to those involving one large and one smaller vessel. In these collisions between large and small ships, it is usually the smaller one that did not properly detect, evaluate, and respond to the threat of collision. This conclusion is illustrated in the example case shown in Appendix D.

A third conclusion is that, for those collisions in which a large ship does not properly detect and evaluate a threat, 70 percent would still have occurred even if a collision avoidance system had been installed. The usual reasons the system would not help are that (1) maneuvers following detection prevent accurate prediction of a CPA or TCPA, or (2) the basic detection capability of the radar was impaired by an obstruction or environmental condition. It may be concluded that a collision avoidance system of the type proposed in Appendix F would not have a very great impact on the total population of collisions.

Finally, based on the mean cost estimates for collisions shown in Table 18 (in the following section describing the collision cause analysis), avoidance of those 25 collisions possibly preventable by a Collision Avoidance Radar System might have saved $3.674 million worth of damage over the 5-year period. At a cost of, say, $150,000 per vessel for installing such systems, it would have been necessary to have installed sets on precisely the 25 vessels involved for the safety benefit to even possibly offset the safety investment. Pending a more careful analysis of the likely practical effectiveness of a Collision Avoidance Radar System, the trends of collision costs, and a discounted cash flow analysis of the required investments and potential benefits, it does not appear that widespread investment in Collision Avoidance Radar Systems would be economically productive.

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COLLISION CAUSES

INTRODUCTION

The previously described analyses demonstrated the application of the Quasi-Experimental Method to evaluation of the effectiveness of collision preventive measures. Those analyses dealt with the relatively small numbers of collision parameters that might be influenced by use of the particular measure under consideration. The analysis of collision causes obviously was more complex. The QEM was applied to develop a gauge for making determinations from the collision reports about the operation of a far more complete set of potential causal factors. This was an exploratory analysis designed to assist in the definition of problem areas in which the Coast Guard may consider and wish to evaluate other preventive measures.

We have developed the collision cause Casualty Analysis Gauge (CAG) in both a structured and flexible manner. Our objective has been to organize the collision factors into relational groupings, and at the same time to form as complete a classification of collision causes as possible from our reading of the collision reports. To realize this objective, we adopted an evolutionary approach in developing the CAG. As we read more and more reports, we continuously improved the questions and the organization of the gauge. Thus the structure of the gauge has been built up in an a posteriori fashion, rather than from a previously designed a priori system of questions. For an example, when an occurrence of ice on the bridge windshield of a vessel obscured vision, and thereby contributed to the collision by causing late detection, it was decided by both readers of the collision reports to add a new alternative to the then existing question no. 20 on late detections. This method alleviated the difficulty of forecasting all collision factors that might appear in the reports in advance.

The problem of ambiguity and inconsistency in the coding of accident reports was discussed in 1951.[1] One study indicated substantial disagreement

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[1] Robert L. Thorndike, "The Human Factor in Accidents with Special Reference to Aircraft Accidents." (Washington, D.C.: U.S. Department of Health,

among codings of accident causal factors not only between different experienced coders, but also between codings of the same accident by the same individual performed at different times. Adaptive coding helps to eliminate ambiguities by allowing the creation of explicit codes rather than forcing a choice among two or more inappropriate codes. Redundant coding allows measurement of coding difficulties and drives the process toward objective representation of the reports. It provides no check on the accuracy of the reports in describing the accident or on the completeness of accident reporting.

Were we to borrow terms from biology, we might describe collision factors by genus, species, and individual cause. For genera we can take the broad categories of mechanical failures, vessel and waterway design, human factors, and environmental conditions. Each generic factor can be broken down into a number of groupings or species of collision factors. Finally, each species can be broken down into individual causes.

For an example, consider a collision where not posting a lookout was a contributing cause. The genus is human factors, the species is violations, and the individual cause is not posting a lookout. Very rarely is a single individual cause the only contributing factor in a collision. Therefore, we have felt no need to assign a single cause to each collision. In the collision cause CAG, a collision is described in terms of multiple factors. An example is illustrated in Figure 16.

In addition to the categories mentioned above, there are other parameters related to individual collisions. They are the type of waterway (ocean, coastal areas, harbors, inland waterways), the rules of the road (International, Inland, Great Lakes, Western Rivers), the scenario (meeting, overtaking, head-on, long range crossing), the visibility, and the time of day. A separate category was set aside for cases in which the presence of a third vessel contributed to the collision. Also, we have made a separate study of the causes of late detection. We study the damage resulting from each collision, as well as the occurrence of hazards or polluting substances aboard the vessels.

The collision cause CAG is presented in Appendix C. An example casualty report is provided in Appendix D, so that the CAG may be considered in relation to the type of record to which it was applied.

The following subsections describe the populations of casualty reports studied in the collision cause analysis, the statistical treatment given the data that resulted from the CAG review of the reports. Then the findings from the analysis are presented. The findings are followed by a brief comment on the limitations of collision cause analysis based on categories derived from the present collision reports. The final subsection deals with new directions for further research.

Education and Welfare, Public Health Service. January 1964 reprint of a February 1951 report to the U.S. Air Force School of Aviation Medicine.)

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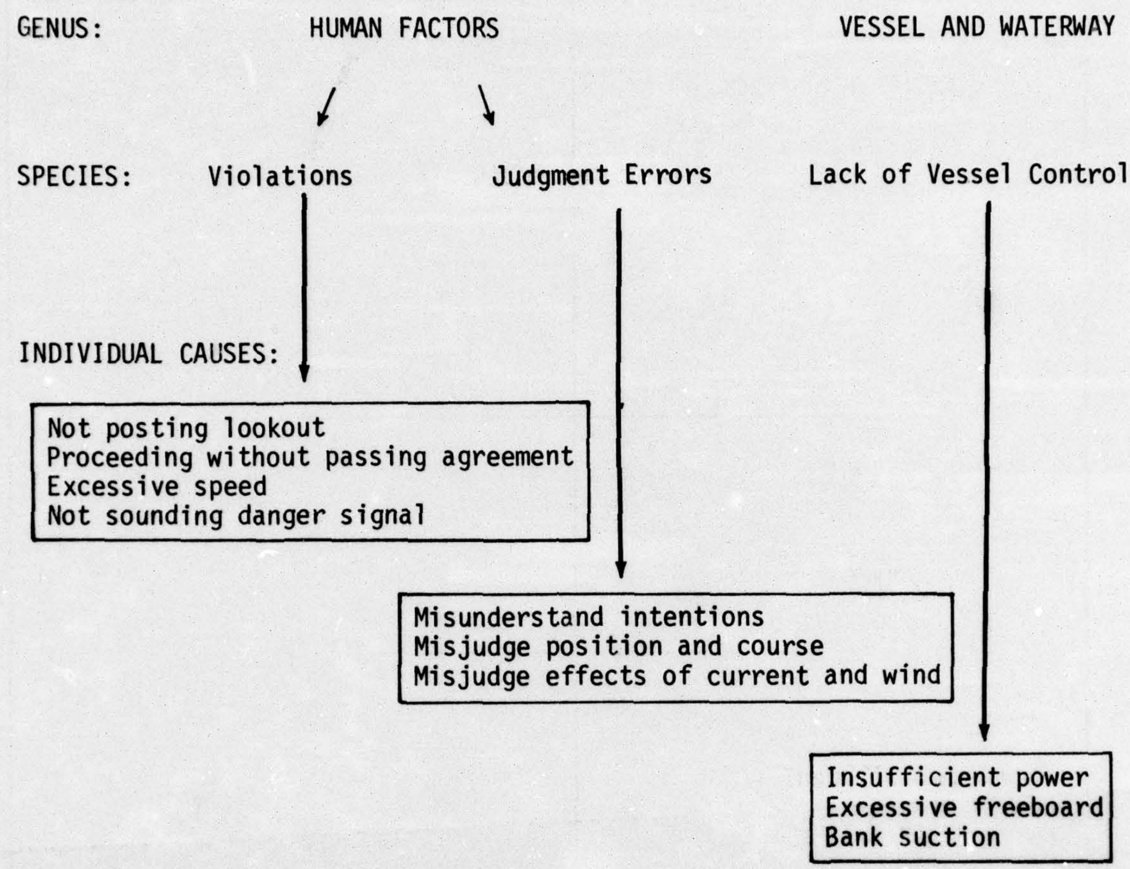

FIGURE 16. EXAMPLE OF COLLISION CAUSE ANALYSIS TREE

POPULATIONS STUDIED

The collision cause analysis addressed two populations: (a) the population of all collisions reported during the 11-year period FY 1964 through FY 1974; and (b) the population (more precisely a subpopulation) of all collisions involving at least one vessel over 10,000 tons that were reported during the 5-year period FY 1970 through FY 1974.

The analysis directed to all collisions from FY 1964-FY 1974 used a 30 percent random sample of collision reports, selected without replacement. This sample includes 525 reports. It is the same sample as used for the analysis of bridge-to-bridge radiotelephone effectiveness, previously presented. (In that case, however, only 436 reports were actually involved—those concerning vessels currently required to be equipped with bridge-to-bridge radiotelephone.) The analysis directed to collisions of the larger vessels from FY 1970-FY 1974 used 100% of the pertinent reports—or 198 reports. This is the same body of reports as was used in the analysis of Collision Avoidance Radar System effectiveness.

STATISTICAL TREATMENT

The incidence of each collision factor, over all years studied, is given as a percentage of the total number of collisions in each population. Since we studied the total population of reported collisions involving a vessel over 10,000 gross tons that occurred in the period studied, the proportions of collision factors in that instance are true proportions of the population. For the 30 percent sample, the porportions of collision factors in the sample are estimates of the true proportions of the population. At a 95 percent confidence level based on sampling without replacement, using a binomial probability distribution, these estimates are valid within an error range of 1.3 percent to 3.6 percent of the population, as can be seen from the Table 8 listing of confidence intervals. Appendix E provides details on the method used for determination of the confidence limits.

TABLE 8

CONFIDENCE INTERVALS FOR COLLISION CAUSE ANALYSIS

Percent of Sample to Which a Collision Factor Contributed	95 Percent Confidence Interval for the Collision Factor
5	3.7 to 6.8
10	8.0 to 12.4
20	17.3 to 23.0
30	26.8 to 33.4
40	36.5 to 43.6
50	46.4 to 53.6
60	56.3 to 63.5
70	66.6 to 73.2
80	77.0 to 82.7
90	87.6 to 92.0

When the percentage incidence of a collision factor in the 100% "sample" fell 5 percent or more outside the confidence limits for the percentage incidence of that factor in the 30% sample, the difference was accepted as statistically significant. We have printed an asterisk by those collision factors found to occur in significantly different proportions in the two populations. For example, the collision factor "Fog" will appear as follows:

	Thirty Percent Sample	One Vessel Over 10,000 Tons
*Fog	19.8%	31.8%

Fog was identifed as a factor in approximately 32% of the collisions involving at least one vessel over 10,000 tons. Fog was identified as a collision factor in about 20% of the 30% sample of all reported collisions that occurred during FY 1964 through FY 1974. The range of probable true values for the sample estimates is, at the 95 percent confidence level, 17.3 to 23.0. The percentage incidence of the factor in the population defined by vessel size exceeds the upper limit of the range by 9 percent. Thus the criterion for significance is met; fog is seen to have figured in the data restricted to collisions involving at least one of the larger vessels more than in the data on the general population of collisions.

CAUTIONARY NOTE REGARDING COMPARISONS

It should be kept in mind that the difference in time periods covered by the two sets of data make generalizations from comparisons of those data open to question. More confidence can be placed in generalizations from the relative incidence of causal factors within the populations than between them.

Comparisons between the two sets of data were made however, as seem useful in an exploratory analysis of this kind. It appears that the incidence of certain factors may correlate with vessel size and/or other parameters such as type of waterway. We could not examine the possible interactions among the identified causal factors and/or possible intervening variables within the scope of this analysis. We were only able, to a limited extent, to identify some possible relationships that may be of interest to future research.

FINDINGS

As noted above, the collision cause CAG was divided into broad categories and then subdivided into individual causes. The presentation of findings follows this general pattern, with the broad categories being addressed first, followed by a more detailed inspection of the individual causes contained within each larger category.

Major Categories Analysis

The findings for this portion of the collision causes analysis are presented in Table 9. Significant differences between the two sample populations occurred in only three categories:

- Vessel and waterway design
- Human factors
- Environment.

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These differences will be addressed in the presentation of the detailed findings for each category.

TABLE 9

FREQUENCY OF COLLISION EVENTS IN THE MAJOR CATEGORIES

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Equipment failures and malfunctions	10.7%	8.0%
*Vessel and waterway design[1]	50.3%	31.3%
Lack of control	19.8%	18.2%
*Human factors	81.9%	89.4%
Violations	60.0%	55.6%
Judgment errors	43.8%	50.0%
*Environment	33.1%	46.5%
Late detection	37.4%	30.0%
Multiple vessels	6.9%	9.5%
Hazardous or polluting cargoes[2]	42.7%	45.5%

[1] It was not practical to separate vessel from waterway design in defining the major categories. See section on vessel and waterway design.

[2] The presence of hazardous or polluting substances aboard the vessels is not to be regarded as a causal factor of collision.

The percentages expressing the incidence of specific factors in each of the major categories do not necessarily sum to the total for the category as a whole. This occurs because more than one of the specific factors often was identifed in an individual collision report. For example "Human factors," a major cause category, were identified as contributing to 81.9% of the cases in the 30% sample. As Table 9 shows, the human factors category is divided into "Violations" and "Judgment errors." In some cases, one or more violations occurred and one or more judgment errors occurred. Thus, when the percentage incidence of violations and the percentage incidence of judgment errors are summed, the total exceeds the percentage of all collisions in which human factors figured as causal. It is also noted that, even where there was only one specific factor of a given category per case, the percentage incidence for the individual factors may not sum to the exact total for the category because of rounding error.

Vessel Equipment Failures and Malfunctions

As shown in Table 9, equipment failures and malfunctions were a contributing cause in 10.7% of the cases reviewed in the 11-year, 30% random sample and in 8.0% of the cases involving a vessel over 10,000 gross tons. This is

not a statistically significant difference. Individual cause findings are presented in Table 10.

TABLE 10

VESSEL EQUIPMENT FAILURES AND MALFUNCTIONS FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Steering failure	3.5%	1.0%
Propulsion failure	2.5%	1.0%
Interior communications equipment failure	0.2%	0.0%
Cable break	2.5%	1.0%
Radar malfunction	1.3%	2.0%
Radio malfunction	0.4%	1.0%
Navigational light malfunction	0.4%	0.0%
Whistle malfunction	0.2%	2.0%

Vessel and Waterway Design

Vessel and waterway design problems were a contributing factor in 50.3% of the collisions in the 30 percent sample and in 31.3% of the collisions involving a ship of over 10,000 gross tons. It was not practical to separate the effects of waterway design from the effects of vessel design since both contribute, in many cases, to a lack of vessel control as can be seen from an examination of Table 11.

In the 30 percent sample, lack of control was a factor in 23.3% of the collisions occurring at bends. Lack of control was a factor in 33.3% of the collisions occurring in narrow channels for this sample. For the collisions involving a vessel over 10,000 gross tons, these proportions are significantly greater, as seen below:

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Percent of bend collisions where lack of control was a factor	23.3%	43.5%
Percent of narrow channel collisions where lack of control was a factor	33.3%	64.2%

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TABLE 11

VESSEL AND WATERWAY DESIGN FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Lack of vessel control	19.8%	19.2%
Insufficient power	6.5%	8.6%
Excessive freeboard	5.0%	2.5%
Bank suction	4.5%	4.1%
Vessel suction	3.8%	4.0%
*Narrow channel	15.0%	7.0%
*Bend	25.3%	11.6%
Channel obstruction	2.5%	1.0%
Other vessel design characteristics	4.4%	0.5%
Other waterway characteristics	3.5%	0.0%

The total numbers of collisions at bends and in narrow channels were as follows for the two sets of data:

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Bends	133	23
Narrow Channels	79	14

Thus, for both populations the problem of vessel control at bends and in narrow channels is considered to warrant further study. Twenty-three percent of the 133 bend collisions in the general population is 31 collisions over the 11-year period. The number for the larger-vessel population is 10, over the 5-year period covered by those data. While the numbers are not large, they are not so small as to be disregarded. Alternatives for reducing such collisions at least should be evaluated in relation to collision costs.

As the preceding data show, although there were fewer collisions at bends and in narrow channels in the population limited by vessel size, that population exhibited control problems in such collisions more frequently. Regulatory restrictions on the maximum size of ocean going ships allowed in certain narrow, winding waterways might be considered as a possible means of reducing collisions of this category. The problem would require further study to determine the feasibility of this type of action. Other contributing causes may have been overriding in the collisions included in this subset.

We will see below that only 2.5 percent of collisions involving a vessel over 10,000 gross tons occurred in Western Rivers. In the 30 percent sample, where 16.2 percent of the collisions occurred in the Western Rivers, the occurrence of collisions at bends and in narrow channels is significant. Below are listed the proportions of collisions in the Inland, Western, Great Lakes, and International waterways that occurred in bends and narrow channels.

	Inland	Western	Great Lakes	International
Bends	26.1%	35.3%	20.0%	2.2%
Narrow Channels	15.0%	21.2%	13.3%	2.2%

We see that the Western Rivers in the 30 percent sample saw a greater porportion of collisions at bends and in narrow channels than the Inland Waterways. The Western River Rules, making the downbound vessel privileged, should have logically been expected to reverse this proportion. A further study should perhaps be made of these collisions to examine this point more closely.

Human Factors

In a lion's share of cases, human factors were cited as causes of collision. In the 30 percent sample, human factors were involved in 81.9% of the collisions. For collisions involving a vessel over 10,000 gross tons, human factors contributed to 89.4% of the collisions. While this difference is statistically significant at the 95 percent confidence level, no conclusion has been drawn as to the underlying reasons for the difference. A summary of the role that human factors played in the two populations is presented in Tables 12 and 13.

We see that the most important violations for collisions involving a vessel over 10,000 gross tons are excessive speed (21.7%), not staying on correct or agreed upon side of channel (16.1%), improper lookout (15.2%), and violating burdened-privileged rule (14.6%). These are also the most important violations for the 30 percent sample, although the violations are more spread out. Excessive speed occurred frequently as a collision cause during reduced visibility, as can be seen by Table 12.

The last mentioned category in Table 13, problems with using bridge-to-bridge radiotelephone, can be further analyzed into a number of contributing factors as follows:

- Not listening to proper frequency
- Too much voice traffic on channel 13
- Difficulties in establishing communications
- Misunderstanding what was said, and misconstruing intentions and agreements
- Mistaking the identity of the vessel with which an agreement was made by radiotelephone
- Not using bridge-to-bridge radiotelephone in situations where it would have helped
- Agreeing to an infeasible passing.

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Further study of this subpopulation might be valuable to find ways to improve bridge-to-bridge radiotelephone communications. For instance, regulations and training to ensure greater circuit discipline could probably help improve the second through fifth of the seven factors shown on the preceding page.

Problems in the use of bridge-to-bridge radiotelephone appear to have undergone an upward trend. Below are the yearly proportions of collisions in which poor use of bridge-to-bridge radiotelephone was a contributing factor:

Year	Thirty Percent Sample	One Vessel Over 10,000 Tons
1964	0.0%	-
1965	3.3%	-
1966	2.5%	-
1967	2.4%	-
1968	3.4%	-
1969	10.3%	-
1970	7.4%	5.7%
1971	10.0%	0.0%
1972	7.5%	9.3%
1973	8.9%	16.7%
1974	17.9%	16.7%

This result is not surprising since, as noted in the bridge-to-bridge radiotelephone QEM findings, no system is faultless. As the use of radiotelephones becomes more general an increase in the number of errors in their use is to be expected.

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TABLE 12

HUMAN FACTORS FINDINGS: VIOLATIONS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Violations	60.0%	55.6%
Improper lookout	14.3%	15.2%
Not attempting to get passing agreement	5.8%	8.6%
Proceeding without passing agreement	5.0%	2.0%
Not sounding fog signal	3.5%	3.5%
Not sounding danger signal	6.9%	6.1%
Not sounding bend signal	5.2%	0.0%
Not sounding overtaking signal	3.3%	2.0%
Not indicating initiation of maneuver	0.2%	1.5%
Not answering request for a passing agreement	2.7%	4.5%
Not staying out of way of overtaken vessel	4.6%	5.6%
Not moving right in a head-on situation	1.7%	2.5%
Not making proper avoidance maneuvers	5.6%	3.0%
Not staying on correct or agreed upon side of channel	12.1%	16.1%
*Burdened-Privileged Rule	6.9%	14.6%
Not giving way to downbound vessel	1.2%	3.0%
*Excessive speed	11.4%	21.7%

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TABLE 12 (Cont)

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Defective equipment	4.0%	7.5%
Unlicensed personnel	1.0%	1.5%
Not monitoring bridge-to-bridge radiotelephone	0.6%	0.5%
Other violations	3.5%	5.1%
Percent of collisions where visibility was less than or equal to a half mile in which excessive speed was a collision cause	38.5%	47.5%

TABLE 13

HUMAN FACTORS FINDINGS: JUDGMENT ERRORS AND OTHER HUMAN ERRORS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Judgment errors	43.8%	50.0%
Position, course of own vessel in channel	4.4%	7.6%
Position, course of other vessel in channel	7.5%	7.6%
Relation in long-range crossing	2.1%	5.6%
Intentions of other vessels	9.3%	7.6%
Maneuver not feasible	7.5%	6.6%
Effects of wind or current	6.2%	5.6%
Illogical maneuver	5.7%	7.1%
Passed closer than necessary	4.8%	3.5%
Maneuvered closer to band than necessary	3.5%	1.0%
Other judgment errors	2.1%	3.5%
Other human factors		
Navigation error	0.6%	1.0%
Poorly given helm or engine order	0.2%	0.5%
Poorly executed helm or engine order	0.4%	1.0%

TABLE 13 (Cont)

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Poor maneuvering	6.0%	3.0%
Inexperience and lack of familiarity with waterway	0.4%	2.5%
Did not hear or misheard whistle signal	3.9%	1.5%
Poor use of radar information	5.4%	7.6%
Inattention	6.3%	8.0%
Misinterpretation of rules of the road	0.6%	0.0%
Problems with using bridge-to-bridge radiotelephone	6.9%	9.1%

Environmental Conditions

Overall, environmental conditions contributed to 33.1% of the collisions in the 30 percent sample and 46.5% of the collisions involving a vessel over 10,000 gross tons. This is a statistically significant difference. The specific conditions occurred as shown in Table 14.

As the final entry in Table 12 indicates, excessive speed was also found to be a contributing factor, along with poor visibility, in a substantial number of cases in both sets of collision data. That combination factor was also observed more frequently in the population of collisions involving at least one vessel greater than 10,000 tons. The larger ships of course have greater speed capability and there may be greater pressure on the personnel of those vessels to maintain speed for economic reasons. This is just one plausible conjecture. We also conjectured that in collisions involving a larger and a smaller vessel, the larger vessel might have greater detection problems than occur when the vessels in an encounter are roughly equivalent in size. That possibility could not be fully evaluated from the data studied, as is indicated in Table 15. Further analysis would be needed to sort out the various possible explanations of the significantly greater incidence of fog- and fog/speed-related collisions involving larger vessels as opposed to the general population of collisions. It is possible that the difference in time period covered by our two sets of data affected the results reported here. Probably more important is the limitation imposed by our scope of work on the sophistication of the analysis. We were not able to explore more complex interaction effects in this effort.

TABLE 14

ENVIRONMENTAL CONDITIONS FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
*Environmental conditions	33.1%	46.5%
*Fog	19.8%	31.8%
Wind	3.7%	3.0%
Currents	8.1%	9.6%
Smoke or haze	0.8%	0.5%
Rain or snow	1.3%	1.5%
Other (ice, shallow water, etc.)	1.3%	1.0%

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Late Detection

Late detections contributed to 37.4% of the collisions of the 30 percent sample, and to 30% of the collisions involving a vessel over 10,000 gross tons. Factors identified as causing late detection are shown in Table 15. The significant difference in the blind bend results seems to be at least partially attributable to the fact that the larger ships have better detection systems and do not spend as much time in narrow, twisting river channels as do towboats and other small vessels. Again, the limitations on this analysis, including the different time base of the data sets, preclude definitive conclusions about the different incidence of this collision factor.

TABLE 15

LATE DETECTION FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Late detections	37.4%	30.0%
Fog or smoke	15.8%	18.2%
*Blind bend	7.9%	0.5%
Bright shore lights obscuring navigational lights of vessel	1.3%	1.0%
Insufficient navigation lights on vessel	2.9%	3.0%
Radar did not detect	1.5%	0.5%
Visual obstruction in waterway	2.5%	1.5%
Inattention	4.6%	4.5%
Vision blocked by tow arrangement or cargo	1.6%	0.5%
Ice or condensation on windows	0.4%	0.5%
Other	2.5%	0.0%

Multiple Vessels

A third vessel contributed to 6.9% of the collisions in the 30 percent sample, and to 9.5% of the collisions involving a vessel over 10,000 gross tons. The effects of the third vessel are given in Table 16.

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TABLE 16

MULTIPLE VESSEL FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Multiple vessels	6.9%	9.5%
Obscuring	0.6%	1.0%
Limiting maneuvering room	2.7%	4.5%
Forced alteration of course	1.7%	2.0%
Led to confusion	1.9%	2.0%

Hazardous and Polluting Cargo

In the 30 percent sample, 42.7% of the collisions involved a vessel carrying a hazardous or polluting substance. For collisions involving one vessel over 10,000 gross tons, this proportion is 45.5%. The frequency of specific substances is given in Table 17. There is very little difference shown between the two populations regarding hazardous and polluting cargoes.

TABLE 17

HAZARDOUS AND POLLUTING CARGO FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Hazardous and polluting cargo	42.7%	45.5%
Oil	23.4%	26.3%
Gasoline	8.3%	6.6%
Liquefied petroleum gas	0.6%	0.5%
Chemicals	10.4%	10.6%
Diesel fuel	1.2%	1.5%

Estimated Collision Cost

A comparison of estimated collision cost in the two populations is shown in Table 18.

TABLE 18

ESTIMATED COLLISION COST FINDINGS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Less than $10,000	52.0%	31.3%
$10,000 to $25,000	20.0%	14.1%
$25,000 to $100,000	13.5%	24.2%
$100,000 to $500,000	6.9%	18.7%
Greater than $500,000	1.7%	5.6%

There is no discernable trend in the cost over the 11 years of the 30 percent sample. However, for collisions involving a vessel over 10,000 gross tons, there appears to be a very sharp increasing trend in collision cost over the 5-year period of 1970 to 1974, as shown in Table 19.

Certainly contributing factors to this trend are increasing repair costs and the increasing average size of the greater than 10,000 gross ton vessels, but increasing speed is also a factor. This parameter refers us back to the human factors analysis, in which excessive speed as a rule violation was shown to be a contributing cause of collision in about 21.7% of the collisions.

TABLE 19

COST TRENDS FOR COLLISIONS INVOLVING AT LEAST ONE VESSEL OVER 10,000 TONS
(K = Thousands of Dollars, M = Millions of Dollars)

	1970	1971	1972	1973	1974
Mean cost	49.00K	37.0K	90.00K	202.00K	205.00K
Median cost	14.00K	30.0K	20.00K	45.0K	44.00K
Total cost	1.63M	1.2M	3.68M	8.7M	7.37M
Number of collisions	35	36	43	48	36

Other Parameters

Other parameters associated with the collision reports that were reviewed are type of waterway, rules of the road, scenario, visibility, and time of day. The proportions of collisions associated with each of these parameters are presented in Table 20.

SUMMARY OF CONSIDERATIONS AND CONCLUSIONS FROM THE COLLISION CAUSES ANALYSIS

Prominence of Human Error in Collisions

Human error was found to be a contributing cause in about 80% of the sample of all collisions in the period studied and in about 90% of collisions involving a vessel over 10,000 gross tons, and arguments could be made for a broader definition of human error than was used in this study. Many mechanical failures are attributed to human error (poor/no inspection and maintenance), and environmental conditions do not inevitably lead to collisions but are only causes if the individuals facing the conditions do not know how to handle them. If the individual accident factors could have been more clearly defined, it seems incontestable that a human error factor would have been found in virtually every accident.

Problems of Making Sense Out of Large Numbers of Human Error Factors When No One or a Few Predominate

The number and disparity of individual error factors indicated by the accident reports was found to be somewhat overwhelming. Upon review of the individual causes, categories ("species") were identified to assist in making sense out of the individual factors. Analysis of those groupings suggests that other groupings may provide greater insight into the human errors associated with accidents and what might be done about those errors.

Two categories of human error factors emerged from this analysis: violations of Rules of the Road and judgment errors. The accident reports indicate (but not conclusively) that violations are rarely the result of not knowing. It appears that violations may proceed from one of the following:

- Ignorance
- Deliberate recklessness
- Carelessness in attention or action
- Judgment that a violation is required by the circumstances (i.e., calculated risk).

Thus at least some violations that result in accidents can be viewed as a subcategory of judgment error.

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TABLE 20

OTHER PARAMETERS ASSOCIATED WITH COLLISIONS

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Type of Waterway		
*Ocean and Great Lakes	8.1%	20.2%
*Coastal areas	3.0%	14.6%
Harbors	8.9%	14.1%
*Interior waterways	80.0%	51.7%
Rules of the Road		
*International	8.8%	35.8%
*Inland	72.2%	57.6%
*Western rivers	16.2%	2.5%
Great Lakes	2.9%	4.0%
Scenarios		
Parallel meeting	34.0%	40.4%
Meeting at a bend	15.0%	8.0%
Parallel overtaking	13.0%	16.7%
Overtaking at a bend	1.2%	2.5%
Parallel head-on	9.2%	3.5%
Head-on at bend	5.2%	1.0%
Long-range crossing	12.1%	19.2%
Other	10.2%	8.6%
Visibility		
Less than ¼ mile	19.7%	24.7%
¼ to ½ mile	3.8%	6.0%
½ to 1 mile	4.0%	3.5%
1 to 2 miles	6.1%	2.5%

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TABLE 20 (Cont)

	Thirty Percent Sample	One Vessel Over 10,000 Tons
Visibility (Cont)		
2 to 5 miles	24.7%	18.7%
Over 5 miles	41.4%	44.4%
Time of Day		
Day	41.7%	49.0%
Night	53.5%	48.0%
Twilight	4.6%	3.0%

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When errors are identified as judgment errors and then reevaluated, it appears that some of them might be attributable to recklessness or to inattention, some to ignorance (no judgment made because no basis for judgment). Some remain as errors in recognizing the possibility of an accident and/or identifying what is required to avoid an accident.

Thus it appears that the following new classification of human errors might prove useful:

- Recklessness or "risk-taking" propensity"
- Carelessness/inattention (where those are not behaviors stemming from recklessness)
- Poor judgment
- Insufficient data, down to no data or ignorance
- Insufficient ability to interpret data.

The content of some of the other categories used in this analysis (e.g., vessel and waterway design, environmental conditions) suggests an additional new category:

- Skills (other than judgment skills) inadequate for successful response to the situation.

This category could include such errors as poor maneuvering and losing control because of current or winds. It brings up an important consideration—what level of skill can reasonably be expected of human beings in different situations? Where the level of skill required is unreasonably high, corrective measures through, say, ship design, channel design, or limitations on operations are indicated.

Limitations of Accident Report Data

The accident reports do not provide enough information to test the utility of the foregoing classifications. Information is needed from individuals involved in accidents to make the interpretations of human errors. The human errors cited in the accident reports are, in a sense, surface effects. To reduce the human error contribution to accidents—and human error is generally agreed to be a primary contributor—it is necessary to get behind the surface effects to sources or causes in people. It is hoped that the sources or causes will be found to be of a manageable number.

Evaluation of this Analysis and Conclusions About Analysis of Human Factors in Marine Accidents

This analysis tried an objective approach, drawing observations from accident reports and investigating their statistical relationships. However, the greatest insights of the analysis were obtained in trying to derive clear, mutually exclusive observation categories from the report so that quantitative analysis could proceed. That effort led to clarification of the <u>range</u> of accident causes. More importantly, it led to the conclusion that additional subjective data are needed from seagoing personnel. Not enough is known about how

they relate to the marine environment and about the attributes of personality, skills, and knowledge that are essential to relating successfully. In the "critical incident technique," as used by J.C. Flanagan (American Institutes for Research), group interviews of personnel involved in accidents and near misses have been conducted as a means of getting below the specific manifestations of human error to understand how they came about. A critical incident survey, properly conducted to assure an appropriate group of respondents, and confidentiality, could, along with other methods, help to clarify the problems of human factors in marine safety.

It would be helpful if further inquiry could be guided by hypotheses about sources of human error as best they can be formulated with current understanding of man-machine-marine relationships. The foregoing set of categories is a first cut at one such hypothesis. Thoses categories, properly developed and modified, mught be used to structure a critical incident type inquiry. They point to four major sources of failure/success in ship control:

- Data input (having the data necessary to make a judgment or execute an action)
- Basic skills (ability to perform the assigned functions satisfactorily)
- Adaptive skills (the ability or abilities that enable a person to respond effectively to changing conditions)
- Personality/situational characteristics that override or impede the positive effects of data input, basic skills, and adaptive skills.

No claim is made that the foregoing concepts should be used to guide further investigation of human factors in marine accidents. The concepts appear promising, but further analysis of available marine accident data, in relation to other pertinent research should be done to develop a structure for further investigation. The area of adaptive skills appears particularly promising. What are the characteristics that result in competency in a given environment? Can environmental characteristics be identified that are associated with specific adaptive behavior requirements? These are questions that might well be asked in some form in any further study of human factors in marine accidents.

PART 3:

THE SCENARIO MODEL

METHODOLOGY AND DEMONSTRATION

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METHODOLOGY AND DEMONSTRATION

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I. INTRODUCTION

OBJECTIVES

The primary objective of this section of the final report is to present extensions to a basic methodology that was originally reported in ORI Technical Report 840, Spill Risk Analysis Program, Phase II, Methodology Development and Demonstration dated 2 August 1974 (AD-785026). The maneuvering analysis previously reported developed the concept of a "collision region" and demonstrated this concept for the parallel meeting scenario and a single collision avoidance maneuver: deceleration. The section of the report contained in the following pages further develops the collision region concept. Additional scenarios such as overtaking, crossing, head-on meeting, and sudden appearance, are addressed. Other collision avoidance maneuvers, such as turning, accelerating, and combinations of course and speed changes, are also included.

A detailed list of the most important modifications to the original model is shown below:

Original Model	Present Model
• Small angle approximations used in computing ships' positions.	• Exact calculations.
• Ships follow circular track when turning.	• More accurate spiral track defined.
• Ships maintain constant speed when turning.	• "Drag" deceleration effects considered.

- Ships are mathematically treated as a point.
- Combined perception and mechanical delay response parameter (ALPHA).

- Ships have length, beam, and pivot point specified. Angle of attack (crabbing angle) is considered in turns.
- Separation of response time lags.
  - Human perception ($Alpha_1$)
  - Ship system ($Alpha_2$).

MODEL APPLICATIONS

The model methodology and the general demonstration of sensitivity analyses presented in this portion of the final report have two principle areas of application. The first is to problems of vessel traffic control where assistance may be needed, in specific areas, by Captains of the Port (COTP) and, in a more general sense, by officers dealing with regulatory problems at the headquarters level. The second addresses problems of vessel controllability and would be primarily useful at the headquarters.

Vessel Traffic Control

When addressing the general problem of vessel traffic control many diverse factors enter into consideration. Channel width and separation, use of communications and other types of electronic systems (e.g. bridge-to-bridge radiotelephone and collision-avoidance systems), modifications to Rules of the Road, and active real-time control (e.g. VTS) are possible ways of dealing with the problem. All contribute to a general long-range Coast Guard perspective. The scenario model described and demonstrated herein is designed to cope with the more easily quantifiable factors in this broad perspective. Sensitivity testing of various initiatives relating to track separation, human perception delays, speeds, and evasive restrictions due to limited maneuvering room can be addressed. A hypothetical example of the manner in which the model might be applied is outlined here for illustration.

Example

The Hudson River main ship channel between Manhattan island and New Jersey is approximately one mile (6000 feet) in width. It is proposed that this channel be divided into two channels, one for northbound traffic and one for south. These two channels are to be separated by a median strip 1000 feet wide. This separation is to be achieved by the placement of two lines of buoys marking the boundaries of the median strip. Let us assume that current traffic in the river, on the average, tends to follow a track near the middle of the east and west sides of the channel (i.e. 1500 feet from both the east and west lines of channel buoys) and that, after the addition

of the two lines of new buoys, traffic will tend to stay toward the center of both the north and southbound channels. If these assumptions are correct, we have then increased the average traffic separation in the river from 3000 feet to 3500 feet. How much is the change likely to reduce the probability of collisions in this portion of New York harbor? By estimating the range of maneuverability of the types of ships that we are most concerned about (i.e. large and small limits on advance, transfer and turning radii), we can use the scenario model to place upper and lower bounds on the decrease in probability of collision. As sensible seamen, we know that this is not a complete answer. The separation area would also tend to assist bridge personnel in the early perception of a potential collision situation (i.e. when an oncoming ship enters the median strip). This effect can also be tested using the scenario model. We have not considered the problem of cross-channel traffic, the probable effects restricting maneuvering room in overtaking situations (also can be tested) and a large number of other factors. We have not completely solved the problem posed by the question, but we have increased our knowledge in relation to one part of the problem and thereby reduced the complexity of the overall situation.

The above is just one example of a single aspect of the vessel traffic control problem which could be analyzed through the use of the scenario model. More examples will certainly result from a thorough knowledge of the operational problems on one side and the maneuver model capabilities on the other. The model will aid in the process of learning from past experience and helps to structure expert judgment in an orderly and quantifiable manner. The interplay of operational experience and model tests will produce an iterative feedback system which will result in new insights. Areas in the modelling process where certain variables are not explicitly treated or need consideration in more scope and depth could be investigated and the overall fund of knowledge thereby increased. The model should be viewed as a tool which helps to answer specific problem solving questions and assists in the exploration of alternative possibilities.

Vessel Controllability

The second area addressed by the maneuvering model is that of vessel controllability. The model explicitly deals with human, as well as mechanical, factors in the chain reaction leading to "in extremis" maneuvering. With increasing numbers of very large bulk carriers, both ships and barges, being constructed, vessel maneuverability (i.e., physical factors relating to vessel motion) and crew controllability (i.e., human factors affecting vessel motion) parameters are changing. Even when these parameters remain constant or are improved in new construction ships and barges, increased traffic density may result in increasing numbers of collisions.

Analyses in this area may improve understanding of various maneuver initiatives (in both design and tactical senses) in differing scenarios. For example, the model can show the relative merits of reducing turning radii, increasing power, and changing evasive maneuvers. These general problems can be viewed in a more specific sense as the value of adding bow thrusters (reduce turning radii), adding another propellor (increased backing power), or, under conditions when it is known that a meeting or burdened vessel (in a crossing situation) is unable to modify its course, turning left to pass under his stern.

ORGANIZATION

This section of the report contains a full technical description of the model methodology showing all concepts included in the model along with their mathematical explication. This model description section is followed by a section demonstrating the type of sensitivity analyses that might be undertaken using the model. The final section contains instructions for the use of the computer program developed for the scenario model.

II. SCENARIO MODEL: METHODOLOGY

INTRODUCTION

Analytic modeling is an ideal supporting tool for a regulatory decision-maker. A model can express mathematical relationships among diverse factors that will permit some measurement of alternatives. It provides sensitivity analyses which reveal, on a strictly comparable basis, the benefits that may be obtained from diverse safety actions such as vessel design changes, traffic control methods, and inferentially, from improvement in certain aspects of human performance. To the extent that uncertainties about the physical processes of an accident are revealed in the modeling effort, sensitivity analyses help to define the relative importance of specific alternative countermeasures.

The level of detail in an analytic model must be sufficient to address accurately the main controllable parameters. Additional levels of detail may be developed for specific parameters shown to be important in the sensitivity analysis.

This section describes the analytic model for vessel collision spills. The following section demonstrates the application of the model to distinguish the risk reduction benefits of various model parameter changes.

The collision spill equation is:

$$N = O \times P(E|O) \times P(C|E) \times P(R|C) \times P(S|R) \qquad (2.1)$$

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where,

O = Number of opportunities [1/]

E = Exposure to collision. An exposure is said to occur if there exists some interval of time during which, if either of the vessels were to make a turn error, a collision would result

C = A collision

R = A hull rupture

S = A spill of a hazardous or polluting substance.

The expected number of collision spills (N) is given by the number of opportunities for exposure to collision (O) times the probability an opportunity will lead to an exposure, $P(E|O)$, times the probability a collision will result from an exposure, $P(C|E)$, multiplied by $P(R|C)$, the probability that a hull rupture will result from a collision and, finally, times the probability a rupture leads to a spill. This analytical method is depicted in Figure 1 by an event sequence tree diagram. All the relevant events occur with some specified probability. The expected number of times that a spill will occur is influenced by each of the conditional probabilities and by the measure of traffic volume and density, O. The analytical maneuvering model presented in this report deals with the factors which influence these conditional probabilities. Figure 2 shows the basic structure of the model.

THE COLLISION REGION CONCEPT

The methodology of the model is based on the concept of a "collision region." A ship is in the collision region if it is on a collision course with another ship and does not have sufficient maneuver capability to avoid collision. The size of the region depends on several parameters, including the physical dimensions of the vessels and their relative speeds and headings.

The collision region is constructed in two steps. The first step is to find the dimensions of the "no change" region. A ship is in the no change region if its course and speed are such that it will collide with another ship. The second step in determining the size of the collision region is to find the portion of the no change region in which appropriate maneuvering could avoid the collision. The final collision region, then, is that portion of the no change region in which collision is unavoidable.

A general collision situation is diagrammed in Figure 3. The vessels have positions x_1 and x_2, lengths L_1 and L_2, with speeds v_1 and v_2, and their

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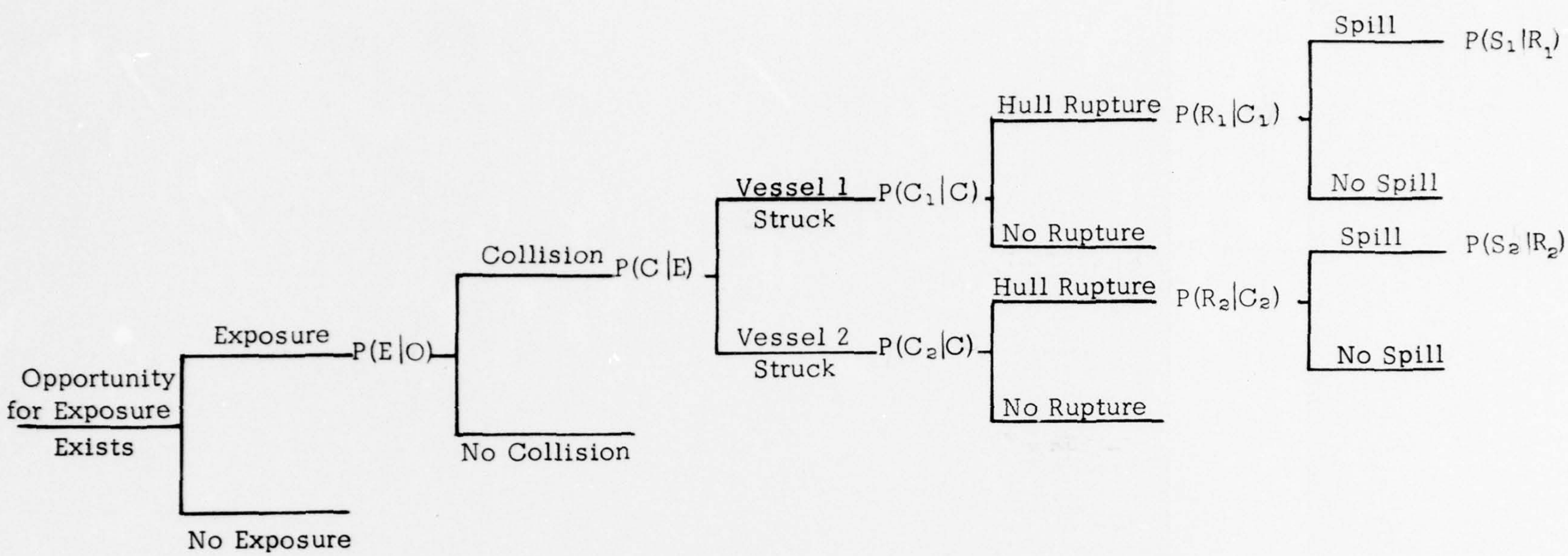
[1/] An opportunity is said to occur when two vessels are present in a channel segment heading either in the same or opposite directions.



$$\text{Number of Opportunities for Exposure} \times P(E|O) \times P(C|E) \times \begin{bmatrix} P(C_1|C) \times P(R_1|C_1) \times P(S_1|R_1) \\ + \\ P(C_2|C) \times P(R_2|C_2) \times P(S_2|R_2) \end{bmatrix}$$

$$0 \times P(E|O) \times P(C|E) \times P(S|C)$$

Expected Number of Spills, N

FIGURE 1. SPILL RISK EVENT TREE

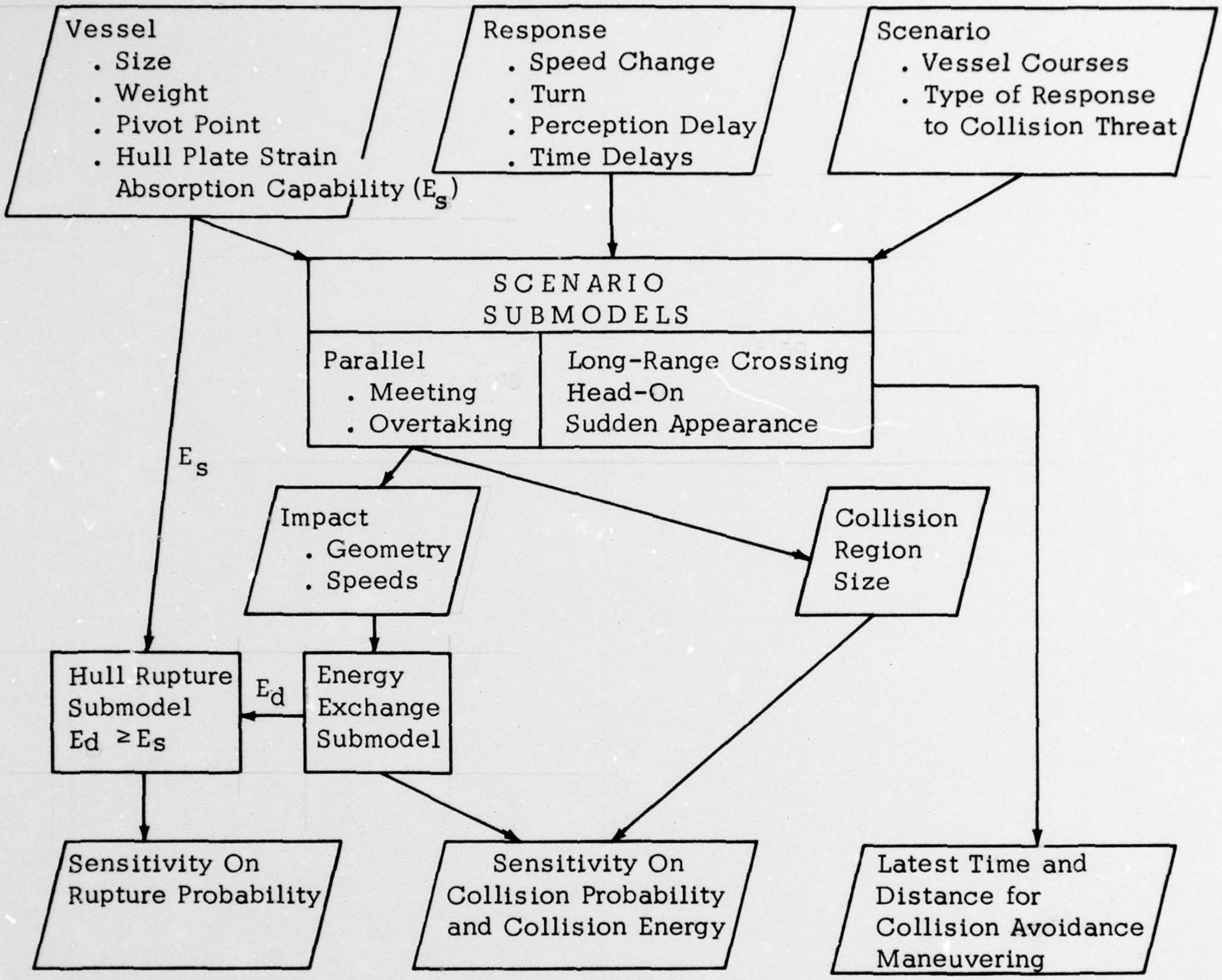
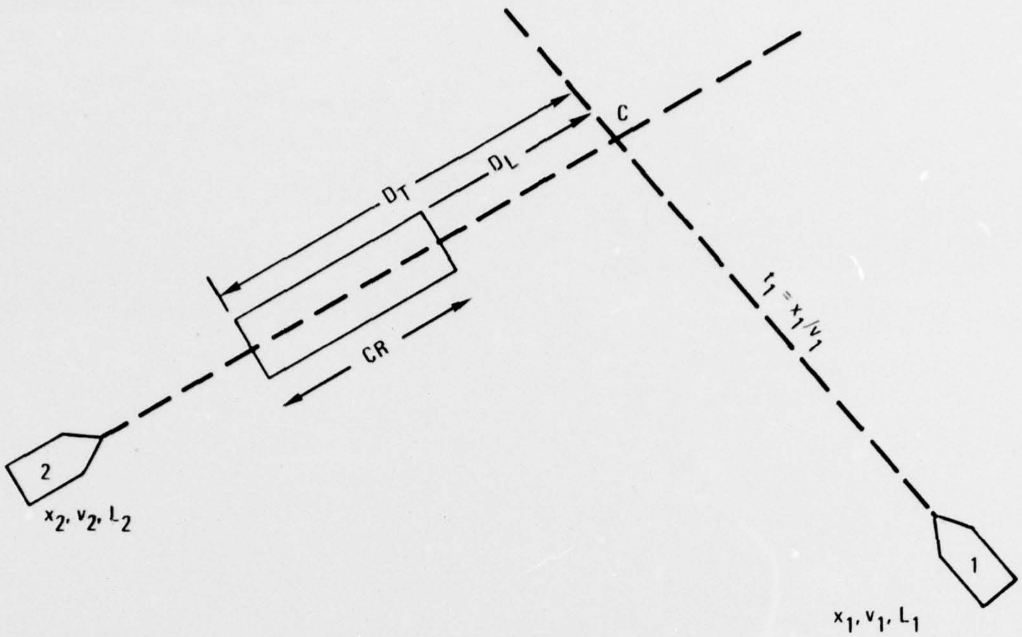


FIGURE 2. SCHEMATIC DIAGRAM OF THE ANALYTICAL SPILL-RISK MODEL



$D_L = t_1 v_2 - L_2$

$D_T = v_2 (t_1 + L_1/v_1)$

$CR = L_2 + v_2 \; L_1/v_1$

If $v_1 = v_2$, then $CR = L_1 + L_2$

FIGURE 3a. GENERAL COLLISION POTENTIAL DIAGRAM SHOWING "NO CHANGE" COLLISION REGION - TIME = 0

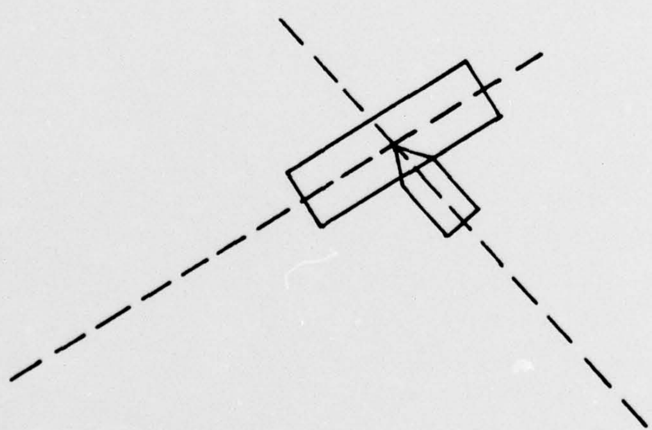


FIGURE 3b. GENERAL COLLISION POTENTIAL DIAGRAM SHOWING "NO CHANGE" COLLISION REGION - TIME = t_1

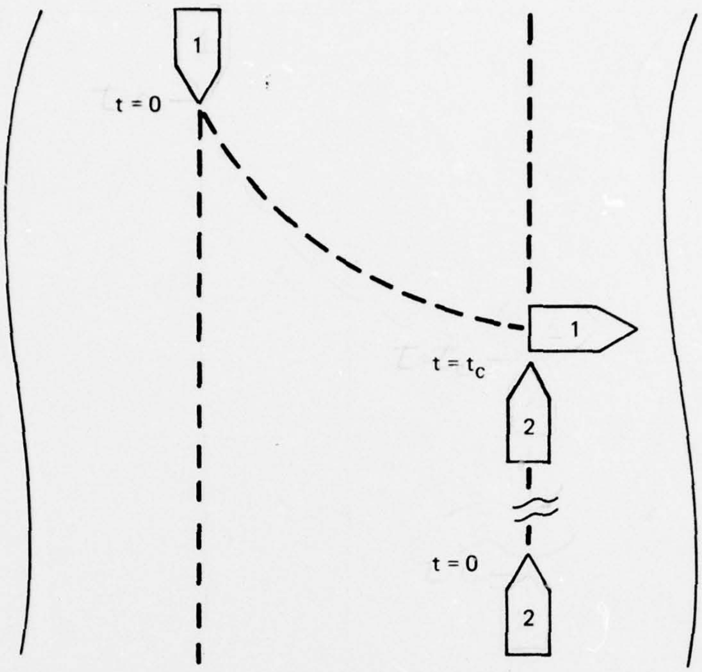


FIGURE 3c. GENERAL COLLISION DIAGRAM FOR THE PARALLEL MEETING SCENARIO

projected paths cross at point C. For simplicity of explanation we will not consider vessel widths. The location and size of the no change region, CR, is determined in the following manner. Let the time required for the bow of Ship 1 to reach the point C be denoted by t_1 where $t_1 = x_1/v_1$. The bow of Ship 2 will also reach the same point at the same time if its bow is located a distance $v_2 t_1$ from C. If Ship 2 had been one ship length, L_2, closer to C then its stern would just be passing C as the bow of Ship 1 reaches that point. Therefore, the leading edge of the no change region is located a distance $D_L = v_2 t_1 - L_2$ away from the point C. To find the trailing edge of the no change region we observe that it takes a time, $\Delta t = L_1/v_1$, for Ship 1 to cross the path of Ship 2. The bow of Ship 2 would therefore have to be located a distance $v_2 \Delta t$ further away from the point $v_2 t_1$ in order to just collide with the stern of Ship 1. The trailing edge of the no change region therefore, is $D_T = v_2(t_1 + \Delta t)$ away from C. The length of the no change region, CR, then is $D_T - D_L = L_2 + v_2 \Delta t_1$ as indicated in Figure 3a. A similar region could be constructed for Ship 1 but we have not shown it in the figure.

As Ship 1 moves toward point C, so does the collision region. When Ship 1 arrives at point C the region will move such that it will be as shown in Figure 3b.

Consider the case where both vessels are going the same speed, $v_1 = v_2$. For the no change collision region, CR is simply the sum of the lengths of the two ships, $CR = L_1 + L_2$. This is true when no course or speed changes are made and if no ship widths are considered. When the widths are used for the calculation of CR, the region will be somewhat larger. For a response such as deceleration the region will become smaller. For a very small deceleration response taken very late, the region will be little different from the no change region. On the other hand, the region will be very small or nonexistent for large deceleration rates and/or an early response. The same is true for a turn response.

The size of the collision region, CR, can be computed as a function of vessel, response, and scenario parameters (z_i) which define the collision situation. The z's are considered the primary variables defining the scenario and the collision region, CR. Examples are: velocity, deceleration, turning radius. These variables are themselves functions of more elementary parameters (y_j), and relations of the form

$$z_i = g_i(y_1, y_2, \ldots, y_m) \tag{2.2}$$

relate the secondary variables (y_j) to the primary variables (z_i). Examples of secondary variables are: ship loading, rudder area, rudder angle. For a given scenario, the size of the collision region is expressed as

$$CR = f(z_1, z_2, \ldots, z_n). \tag{2.3}$$

The scenario which is considered in greatest detail in this report is that of a parallel meeting of two ships in a restricted channel. The collision region under this scenario is developed in the following fashion using the diagram of Figure 3c. We shall call vessel 1 the "intruder" and vessel 2 "own ship." (This convention with vessel 1 being the initiator of a collision situation and being depicted as heading down from the top of a diagram is generally used throughout this report.)

If the intruder starts its turn at time 0 it will just miss own ship by crossing ahead at some later time, t_C. If the intruder begins its turn at a time before time 0, no collision will result. If the turn begins shortly after time 0, own ship will strike the starboard quarter of the intruder. As the time of turn increases beyond time 0, the point of collision moves up the starboard side of the intruder until the two ships would meet bow to bow. Beyond this point in time, the point of collision will move down the port side of own ship until the intruder just misses own ship by passing under our stern. The length of the collision region is therefore the locus of points occupied by own ship's bow between a time zero when an intruder turn would result in a near miss with the intruder crossing close ahead of own ship and a later time when the

intruder turn would result in a near miss with the intruder passing close aboard under our stern. Given any two ships meeting in a channel, this dangerous period (own ship in collision region) is fixed so long as own ship takes no collision avoidance action. When own ship takes no avoidance action, the "no change" collision region is defined. The size of the collision region will be changed by any avoidance actions that may be taken.

In Figure 3a the equation for CR is explicitly stated. However, when widths and a response are taken into consideration it is no longer possible to give an explicit solution in closed form. Rather, the conditions for the collision region are mathematically stated and a computerized numerical process is used to arrive at the solution.

THE SCENARIO SUBMODELS

There are two basic models of vessel interaction which apply to all known situations involving pair-wise collision-threat situations. First, there is the parallel meeting and overtaking scenario—the restricted waterways model. Second, there is the long-range crossing scenario involving ships on intersecting courses—the open waters model. From these two basic models, input modifications can simulate any possible type of two-ship interaction. The "head-on" and "sudden appearance" models are two such special scenarios.

The head-on scenario is a special case of the parallel meeting siutation where there is no separation between the tracks of the two vessels. In the basic meeting case, the vessels are on opposite headings and on straight line parallel tracks separated by a distance, S. A collision can only occur if one of the two ships deviates from its course. In the head-on scenario, a collision will occur if one of the two ships does <u>not</u> deviate from its course (or if both ships do not stop before reaching the collision point).

The sudden appearance scenario is a special case of the long-range crossing situation in which the desired answers are identical, but the questions differ. In the long-range crossing, a stand-on, or privileged, vessel has an early awareness that it is on a collision course with another vessel and wants to know the time of its last chance to maneuver. On the other hand, the sudden appearance analysis is aimed at determining how late a vessel may discover that it is on a collision course and still safely maneuver to avoid collision.

<u>Parallel Meeting and Overtaking</u>

The parallel meeting scenario, as characterized briefly above, involves two vessels travelling on reciprocal courses in a channel. Let us consider a channel segment of length L having a suitable and uniform width such that the two vessels will have projected parallel paths some distance, S, apart. While traversing the channel segment, there will either be a normal passing or a collision. Should a collision situation arise, it can only occur if one of the two vessels executes a turning maneuver and continues on this turn without correction. In this report we do not model the events which lead to this turn maneuver. It can be the result of malfunctions, either human or mechanical, which are irrelevant in this analysis. The assumption is made that a turn maneuver may occur at a random time while in the channel.

An important assumption within the model is that the probability that such a collision-causing maneuver occurs is a function not of speed but of distance travelled. For a doubling of the distance that a vessel travels, the probability that the turn maneuver described here will occur will be doubled. Thus, the probability of a collision is a product of the probability of the maneuver error per unit distance times the distance that vessel travels in which an error <u>would</u> produce a collision.

There is some difficulty in settling on a measure of the turn error probability. First, it is assumed that the cause of collision in a channel is a result of one vessel, in a parallel track pair, making a turn at some point. This turn is a normal turn with no engine order and with a constant rudder angle. Secondly, the error rate is not a function of one specific error or error set, but may be a result of any of several errors or error sets. The cause of the turn error may be an equipment problem, a behavioral problem or a shiphandling problem in which wind and current effects, the vessel design and its control mechanisms, and the range of skills over the operator population or of one operator over time, are sufficient to cause some probability of collision.

Clearly an important concern is that the error rate, even accepting a "turn error with unknown cause" concept, may be dependent on some of the system parameters in this model. Velocity is surely a factor in the determination of our error event. While operating in a speed range in which adequate steering control is possible, quicker responses must be made while moving at higher speeds in order to keep the vessel on a desired track. If one uses an error rate which is time-dependent the result would show that moving faster reduces errors, (but not necessarily the probability of collision). On the other hand, when choosing a distance-dependent error rate, the result would be that errors were more frequent at higher speeds. This statement assumes that a pilot or ship's officer is equally likely to make an error at any point in time. With a faster moving vessel, the consequence of this error is more likely to result in a full turn across the channel than at a slower speed. That is, within a range of adequate steering control, a vessel is more likely to stay on course at slower speeds because the available reaction time to make course corrections is greater. At higher speeds, operator reflexes may be just as fast, however the vessel will move further across the channel, and the chance of course correcting behavior is less likely to be sufficient to avoid collision.

One could argue that the error rate is reduced when the pilot elects to increase speed, and the chance of performing the turn-maneuver error is closer to being equally likely at any speed—as would be described by a time based error rate. Nevertheless, until further research produces better information about the nature of how and why a ship's officer/pilot and his vessel act together to cause a collision, our assumptions are:

1. Collisions in a channel are caused by one of a pair of vessels turning across the path of the other

2. The rate of making this turn-maneuver error is such that an event occurs with equal likelihood during any uniform travel distance.

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Note that not all of the sensitivity analyses presented in the following section are dependent upon the time versus distance assumptions in the error rate. For example, the effect of better maneuverability can be tested assuming either an error rate per unit time or error rate per unit distance and achieve the same results, since the terms in the sensitivity equation which would differ cancel out either way. Velocity sensitivity, on the other hand, is not quite so robust—the terms which differ are very important.

To return from this digression on the error rate, we now consider the parallel overtaking scenario. Again, we start out with a channel segment of length L. It is assumed that both vessels will be in the channel at some time. Now, however, the chance of being exposed to a possible threat is not a certain event as is the case in the meeting scenario; the overtaking vessel must catch the slower vessel first. Given that the slower vessel being overtaken is caught, there is a chance for either vessel to make an error in maneuvering (of the same type as for the meeting case) and have a collision result.

Let us now look at the parallel scenario in more precise terms and arrive at an expression for the number of spills expected, N, for a channel segment in which two vessels are in the channel a number of times, O. We have again the collision spill equation (2.1):

$$N = O \times P(E|O) \times P(C|E) \times P(R|C) \times P(S|R)$$

where $P(E|O)$ is the conditional probability of an exposure given an opportunity for exposure, O, exists.

$$P(E|O) = \begin{cases} 1 & \text{for parallel meeting} \\ \left.\begin{array}{ll} 1 - \dfrac{v_2}{v_1}, & v_1 > v_2 \\ 1 - \dfrac{v_1}{v_2}, & v_1 < v_2 \end{array}\right\} & \text{for parallel overtaking.} \end{cases} \qquad (2.4)$$

It is clear in the meeting case that if two vessels are in a channel they will have to pass each other. However, in the overtaking case this certainty of exposure does not exist.

We say that at time $t = 0$, Ship 2 is in a channel segment of length L (see Figure 4). It may be at any position in the channel at $t = 0$ with equal likelihood. Or, in other words, its probability of being at any position in the channel segment $(0, L)$ is described by a uniform density function. Ship 1 enters the channel at position 0 at time $t = 0$. In order to pass Ship 2 before

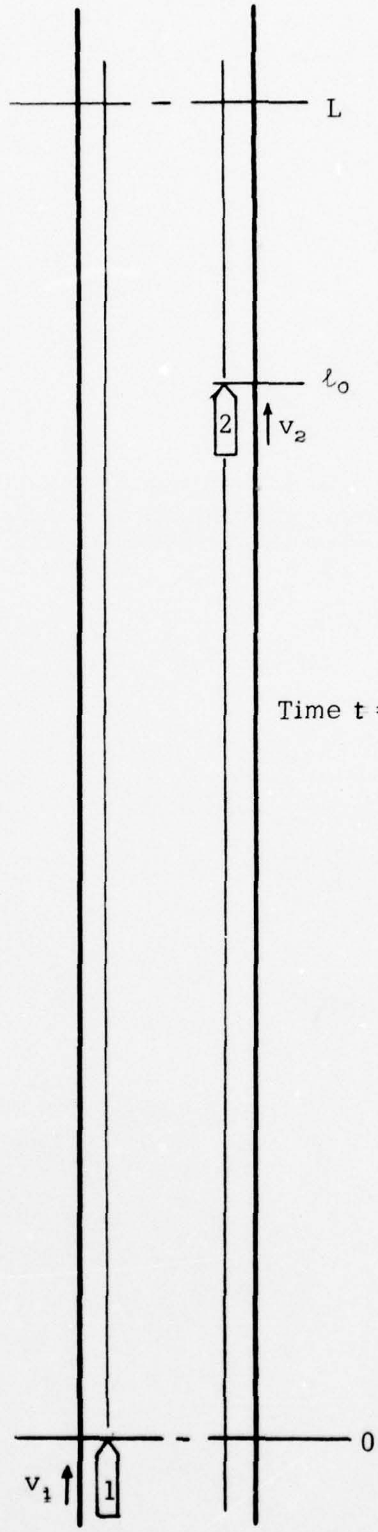

FIGURE 4. PARALLEL OVERTAKING

it leaves the channel, Ship 1 has to travel distance L in at least the same time required for Ship 2 to travel distance $L - \ell$. Thus, v_1 must be large enough or ℓ must be small enough such that

$$\frac{L}{v_1} \le \frac{L-\ell}{v_2}, \tag{2.5}$$

where L/v_1 is the time it takes Vessel 1 to traverse the length of the channel and $(L - \ell)/v_2$ is the time for Vessel 2 to reach the end of the channel from its initial position. Thus, solving for ℓ in Equation (2.6) we get ℓ_o—the furthest distance Vessel 2 can be from the start of the channel and still be caught.

$$\ell_o = L\left(1 - \frac{v_2}{v_1}\right). \tag{2.6}$$

Or, with given velocities of Vessels 1 and 2 and a channel length of L, Vessel 1 can overtake Vessel 2 as long as Vessel 2 is no further than distance ℓ_o ahead in the channel.

Then to calculate the probability of exposure, $P(E|O)$, given that Vessel 2 will be somewhere in the channel when 1 enters, we want to know

$$P(\ell \le \ell_o) \equiv P(E|O). \tag{2.7}$$

Since ℓ is uniformly distributed on the interval $(0, L)$ and

$$P(\ell \le \ell_o) = \begin{cases} \frac{\ell_o}{L} & \text{if } 0 \le \ell_o < L \\ 0 & \text{if } \ell_o < 0 \\ 1 & \text{if } \ell_o \ge L \end{cases} \tag{2.8}$$

we may conclude that:

$$P(\ell \le \ell_o) = \frac{\ell_o}{L} = \frac{L\left(1 - \frac{v_2}{v_1}\right)}{L} = 1 - \frac{v_2}{v_1} \tag{2.9}$$

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where

$$\ell_o = L\left(1 - \frac{v_2}{v_1}\right).$$

Hence,

$$P(E|O, \text{ overtaking scenario}) = 1 - \frac{v_2}{v_1} \qquad (2.11)$$

when $0 \leq \ell_o < L$ and $v_1 > v_2$. Note that as the overtaking velocity v_1, becomes greater, so does the probability of exposure.

Moving on to the probability of collision given exposure, $P(C \mid E)$, the equations that have been used in this analysis assume channel lengths which are much longer than the length of a collision region. The rationale for this decision follows.

If we have a vessel 1 proceeding into a channel of length L at a speed of v_1 knots and a vessel 2 making v_2 knots enters the channel from the opposite end, a meeting situation will result prior to their exit if they both proceed directly through. The question is how to compute the probability of collision in the channel.

Using the following parameters:

q = empirical rate per unit distance traveled at which a set of circumstances will result in a turn leading to a potential collision

L = length of the channel

v_1 = speed of vessel 1

v_2 = speed of vessel 2

$V = v_1 + v_2$

a = distance of front of collision region from bow of vessel 1

b = distance of trailing edge of collision region from bow of vessel 1

$b - a$ = length of collision region.

These quantities are illustrated in Figure 5. If we let vessel 1 enter the channel at time zero, then vessel 1 would normally exit from the channel at time L/v_1. We let T be the random time that vessel 1 veers across the channel. The condition that vessel 1 veers in the channel is the condition

$0 \leq T \leq L/v_1$. We assume that the random variable T is uniformly distributed over the interval $[0, L/v_1]$.

We let Y be the random position of vessel 2 at time zero. The condition that the two vessels meet in the channel is the condition $0 \leq Y \leq VL/v_1$. We assume that the random variable Y is uniformly distributed over the interval $[0, VL/v_1]$. We then let $y_1(t) = v_1 t$, and $y_2(t) = Y - v_2 t$ give the positions of the two vessels at time t. Then the conditional probability P(T) of collision, given that vessel 1 veers across the channel at time T, is given by

$$P(T) = P\{y_1(T) + a \leq y_2(T) \leq y_1(T) + b\}$$

$$= P\{VT + a \leq Y \leq VT + b\}$$

$$= \begin{cases} \dfrac{b-a}{L}\dfrac{v_1}{V} \\ \text{if } 0 \leq T \leq \dfrac{L}{v_1} - \dfrac{b}{V} \\ 1 - \dfrac{a}{L}\dfrac{v_1}{V} - \dfrac{v_1 T}{L} \\ \text{if } \dfrac{L}{v_1} - \dfrac{b}{V} \leq T \leq \dfrac{L}{v_1} - \dfrac{a}{V} \\ 0 \text{ otherwise.} \end{cases}$$

We then have

$$P_{(C|E)} = q \int_0^{L/v_1} P(T) \frac{v_1}{L} \, dT$$

$$= q \frac{v_1}{V} \frac{b-a}{L} \left[1 - \frac{b+a}{2L} \frac{v_1}{V}\right] \qquad (2.11)$$

If the channel length L is great relative to the b + a term, then the term $(b+a)\, v_1/2LV$ is not significant and

$$P_{(C|E)} = \frac{q}{L} \frac{v_1}{V} (b-a)$$

$$= q \frac{v_1}{V} (b-a) \qquad (2.11a)$$

where q can be defined operationally as the empirical frequency of veerings across channels divided by the length of the channels for all channels in a broad sample.

The reason the probability for collision in a finite channel is less than for an infinite channel is that the condition of meeting in the channel precludes certain collisions beyond the ends of the channel caused by veering in the channel. Thus it would seem that the infinite channel is a better model.

The operational definition of q frees it from dependence on channel width, depth, etc. However, by grouping channels into widths or depths, and conducting experiments on the subpopulations, we can get q's that depend on these kinds of parameters as well. Always q represents the amount of knowledge we have gained from experiment. q only depends on the other parameters when we have the information. Otherwise, it should only reflect the information we do have. Probability is a relative concept depending on the state of our ignorance by definition.

Next we have

$$P(C|E) = 1 - e^{qD} \approx qD = q(D_1+D_2)$$

$$= q(v_1 \, TCR_1 + v_2 \, TCR_2) \qquad (2.12)$$

where,

q = An empirical rate as defined in the previous paragraphs

D_i = Distance travelled during which the error in turning by vessel i produces a collision (see Figure 5a)

$D = D_1 + D_2$

CR_i = Length of collision region i

TCR_i = Time in collision region (i.e., time other vessel exposed to a potential collision caused by vessel i)

$$= \begin{cases} \dfrac{CR_i}{v_1+v_2} & \text{for parallel meeting} \\[2ex] \dfrac{CR_i}{v_1-v_2} & \text{for parallel overtaking and } v_1 > v_2. \end{cases}$$

Equation (2.12) is obtained as an approximation of the equation for the exponential distribution. This distribution is appropriate because of the assumption that the rate at which the turn error is made is constant. In the literature of reliability theory the notion of "failure" is used. Then, when a system or a component of a system has a failure rate which is constant, the Exponential Failure Law applies. According to this law, the time to failure

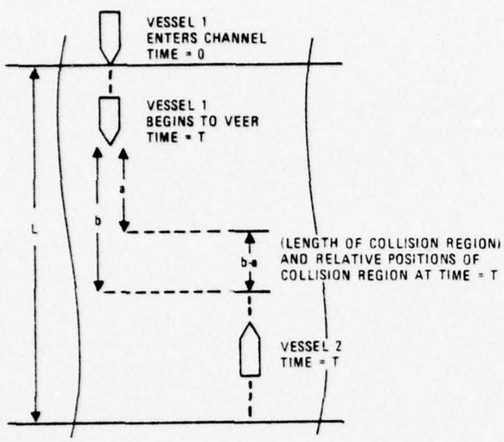
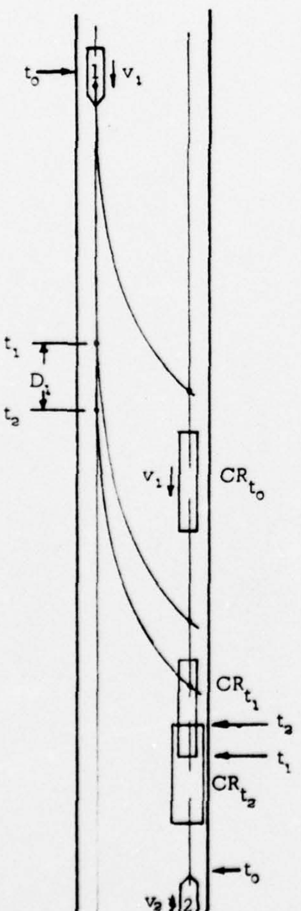


FIGURE 5. COLLISION REGION - FINITE CHANNEL PARAMETERS



For a given pair of vessels traveling on parallel tracks with reciprocal headings, there is a distance D_1 during which a turn by Vessel 1 would produce a collision—either striking or being struck. The collision regions shown (at times t_0, t_1, and t_2) are those corresponding to a turn by Vessel 1 at the indicated positions. For a turn by 1 between times t_1 and t_2, Vessel 2 would be somewhere in a collision region. Before t_1, Vessel 2 would be behind the collision region and after t_2 would be in front of it. (Note: a) the arrows represent positions of Vessel 2 bow and Vessel 1 pivot point; b) larger width of CR_{t_2} is only for differentiation from CR_{t_1}.)

FIGURE 5a. PICTORIAL REPRESENTATION OF THE DEVELOPMENT OF DISTANCE "D_1" IN EQUATION (2.12) FOR THE PARALLEL MEETING SCENARIO

is a continuous random variable assuming all nonnegative values. T, the life of the system or component until it fails, has an exponential distribution if and only if it has a constant failure rate. This theorem is expressed as

$$P(t \le T \le t + \Delta t | T > t) = 1 - e^{-q\Delta t}. \qquad (2.13)$$

In this equation the probability of failure, given a failure rate q, is expressed in terms of an interval of time, Δt, in the life of the system or component, and does not depend on t, the age. In other words, for the same Δt, the probability of failure is the same when new as when old.

In our application t is replaced by ℓ, the distance travelled in a channel where $\Delta\ell$ is defined as D, and system "failure" is interpreted to be the turn error.

For the exponential distribution equation the Mclaurin series is

$$1 - e^{-qD} = qD - \frac{(qD)^2}{2!} + \frac{(qD)^3}{3!} - \dots . \qquad (2.14)$$

For a sufficiently small q and D the approximation

$$1 - e^{-qD} \simeq qD \qquad (2.15)$$

may be made. If this approximation is used in our analysis it is not necessary to estimate the value of q, since in the sensitivity analysis a ratio is computed in which q may then be cancelled out of the expression as long as it remains constant.

To estimate the error in using the approximation let us consider an example. Since the expected value of the travel distance to experience a turn error for this distribution is $E(D) = 1/q$, let us assume that $E(D) = 10$ miles. Thus $q = 1/10$ mi $= 1/60,760$ ft $= 1.65 \times 10^{-5}$/ft, the error rate per foot. Then, from our experience, the worst value of D to be encountered is calculated from

$$D = D_1 + D_2 = (v_1 CR_1 + v_2 CR_2)/(v_1 + v_2) \qquad (2.16)$$

where $CR_1 = CR_2 = 3,000$ ft and $v_1 = v_2$. Thus, $D = (3,000 + 3,000)v_1/2v_1 = 3,000$.

From the exponential distribution the probability of collision in this case is

$$P(C|E) = 1 - e^{-qD} = 1 - e^{-(1.65 \times 10^{-5})3,000} = .0482. \qquad (2.17)$$

With the approximation, $P(C|E) \simeq qD = .0494$. The difference in the answers is 2.5 percent. This would be for a parameter change in which a very long

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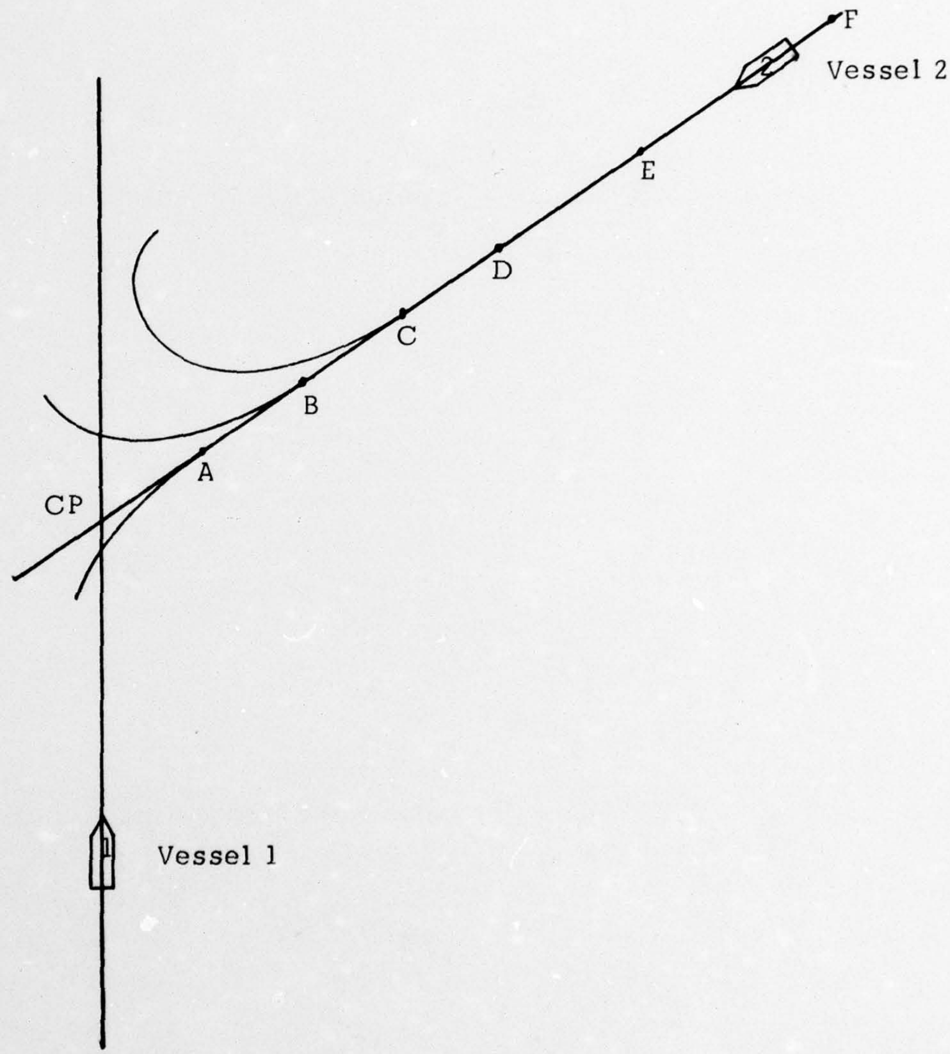

FIGURE 6. LONG-RANGE CROSSING AND SUDDEN APPEARANCE—POINTS AT WHICH MANEUVERS MUST BE INITIATED TO AVOID COLLISION

collision region is reduced to zero. More likely is the case of a smaller percentage change in a much smaller initial region. Thus, the approximation error would be less than this 2.5 percent.

To continue with our discussion of the factors in the collision spill equation:

$$P(R|C) = P(E_d \geq E_s) \qquad (2.18)$$

where

E_d = Energy of collision which must be absorbed by hull plate and web frame structure of colliding vessels (deforming energy)

E_s = strain energy level at which hull plate will rupture.

There are four standard situations for any scenario. First consider Vessel 1 causing the collision. Then Vessel 1 may strike Vessel 2 or be struck—two cases. Second, Vessel 2 may cause the collision and either strike or be struck—two more cases. When considering rupture, each of the four cases is independently analyzed and

$$P(R|C_i) = \frac{NR_i}{N} \qquad i = 1, 2, 3, 4 \qquad (2.19)$$

where C_i collision type is:

C_1 = Vessel 1 erred and strikes 2 (the front portion of CR_1

C_2 = Vessel 1 erred and is hit (the rear portion of CR_1)

C_3 = Vessel 2 erred and strikes 1 (the front portion of CR_2)

C_4 = Vessel 2 erred and is hit (the rear portion of CR_2)

N = Arbitrary number of points in each C_i for which the collision energy, E_d, is computed and compared to strain energy of hull rupture, E_s, of struck vessel

NR_i = Number of times $E_d \geq E_s$ out of the N collisions computed in case i.

Next is:

$$P(S|R_i) = P(HPS_j) \qquad (2.20)$$

where

$P(HPS_j)$ = The probability that vessel j is carrying a hazardous or polluting substance. For i = 1 or 4, j = 2; and for i = 2 or 3, j = 1.

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Returning to the full collision spill Equation (2.1) again, we have

$$N = O \times P(E|O) \times P(C|E) \times P(R|C) \times P(S|R).$$

For the parallel meeting case we use Equations (2.5), (2.12), (2.18), (2.19), and (2.20) to get

$$N = O \cdot 1 \cdot qD \cdot P(E_d \geq E_s)P(HPS) \tag{2.21}$$

$$= O \cdot 1 \cdot q \sum_{i=1}^{2} v_i TCR_i P(E_d \geq E_s)P(HPS) \tag{2.22}$$

$$= O \cdot q \sum_{i=1}^{2} v_i \frac{CR_i}{v_1 + v_2} P(E_d \geq E_s)P(HPS) \tag{2.23}$$

$$= O \cdot q \left[D_1^F \frac{NR_1}{N} + D_1^R \frac{NR_2}{N} + D_2^F \frac{NR_3}{N} + D_2^R \frac{NR_4}{N} \right] P(HPS) \tag{2.24}$$

where

D_1^F = Distance Vessel 1 travels during which, if it has made *the turn error, Vessel 2 would be struck, F—refers to* the front portion of the collision region. Subscript *refers to* CR_1

D_1^R = Distance Vessel 1 travels where turn error would result in its being struck by 2, R—rear portion CR_1

Etc.

q = The rate per unit distance travelled at which a set of circumstances will combine to produce a turn leading to a potential collision.

For the parallel overtaking scenario we combine Equations (2.5), (2.12), (2.18), (2.19), and (2.20) to get

$$N = O\left(1 - \frac{v_2}{v_1}\right) qDP(E_d \geq E_s)P(HPS) \tag{2.25}$$

$$= O\left(\frac{v_1 - v_2}{v_1}\right) q \left(v_1 \frac{CR_1}{v_1 - v_2} + v_2 \frac{CR_2}{v_1 - v_2}\right) P(E_d \geq E_s)P(HPS) \tag{2.26}$$

$$= O \cdot q \left(CR_1 + \frac{v_2}{v_1} CR_2 \right) P(E_d \geq E_s) P(HPS) \qquad (2.27)$$

$$= O \cdot q \left[CR_1^F \frac{NR_1}{N} + CR_1^R \frac{NR_2}{N} + CR_2^F \frac{v_2 NR_3}{v_1 N} + CR_2^R \frac{v_2 NR_4}{v_1 N} \right] P(HPS). \qquad (2.28)$$

The expression in brackets in Equations (2.24) and (2.28) is that which is evaluated in the sensitivity analysis to be discussed in the next section.

Long-Range Crossing

As mentioned earlier, the methodology of the long-range crossing scenario utilizes a somewhat different approach. The collision region concept is used, but the viewpoint is different. Two vessels are said to be on courses such that if neither vessel were to maneuver there would be a collision. The burdened, or give-way, vessel is required by the Rules of the Road to maneuver. The situation is analyzed from the viewpoint of the privileged, or stand-on, vessel. Decisions must be made under an assumption that the burdened vessel may not maneuver to avoid collision as required. We begin with the ships already in a collision region and analyze the effects of various maneuver options in completely eliminating the probability of collision (i.e., reducing the size of the collision region to zero).

Another difference in this scenario is that the vessel is in the collision region to begin with, and we conservatively assume that for the given response it is in the worst place in the collision region.

Figure 6 illustrates this scenario. Vessel 2 is the privileged, or stand-on vessel. Since it is on a collision course with Vessel 1 it is in a collision region. Vessel 2 wants to wait, of course, for Vessel 1 to maneuver, since that is the responsibility of Vessel 1. However, Vessel 2 is interested in information about the situation, and how it will develop, should Vessel 1 fail to maneuver to starboard as he should. With our assumption of conservative analysis and since it is not known where in the collision region Vessel 2 happens to be, assume that he is at the front. Thus, if he were just slightly ahead of that position he would pass safely ahead of Vessel 1, as long as Vessel 1 continued on its present course. The captain of Vessel 2 now wants to know when he would have to maneuver in order to avoid collision with Vessel 1 (assuming 1 does not maneuver).

As indicated in Figure 6, Vessel 2 would have to begin stopping at point F in order to come to a complete halt before arriving at the intersection C.P. If he began decelerating at point E, and Vessel 1 does not maneuver, he will slow enough to pass astern of Vessel 1. If he waited until point D and performed a rudder cycling maneuver the same would happen. However, if he waited until point C decelerating would no longer ensure avoiding a collision. Now he would have to turn (which results in a very large deceleration effect). Had he turned right at point C, he would never cross the projected path of Vessel 1. Points, E, D, B, and A, in contrast, represent the starting position of maneuvers which will lead to crossing the path of Vessel 1 but safely behind him. If he waited to respond until point A and for some reason was very sure that Vessel 1 was not going to turn right and/or slow down,

as he is supposed to, a left turn would allow him to avoid collision. The left turn, while contrary to the Rules of the Road and dependent on Vessel 1 keeping to his straight course, is included for comparison purposes and to complete the analysis.

For the first case, in which Vessel 2 avoids crossing the path of Vessel 1, closed form solutions of the distance to collision point and TCPA at which maneuvering must begin may be derived. For stopping, the equation $v = f(t)$ is solved for t_0 where $f(t_0) = 0$. With that t_0 (TCPA) the distance to collision, $t_0 v_2$, may be calculated.

For the right turn the distance is calculated with the spiral turn parameters A and B and the angle of crossing, γ. Figure 7 illustrates the situation geometry. The distance from collision at which the turn must be initiated is

$$D = B + G = B + \frac{A}{\tan[(180 - \gamma)/2]} . \tag{2.29}$$

To simplify the expression for closed form solution and to incorporate a margin of clearance for safety, A is used as the measure of distance from the turn circle center to the projected path of Vessel 1. The actual distance of any point on the spiral path to the turn circle center is $R(\theta)$ where $\theta = g(t)$. Since $\lim_{t \to \infty} R(g(t)) = R$ and since $A = aR$ where a is slightly greater than 1 (e.g., $a = 1.15$) $R < R(g(t)) < A$. Hence, A is used for simplicity and safety. TCPA is then calculated to be

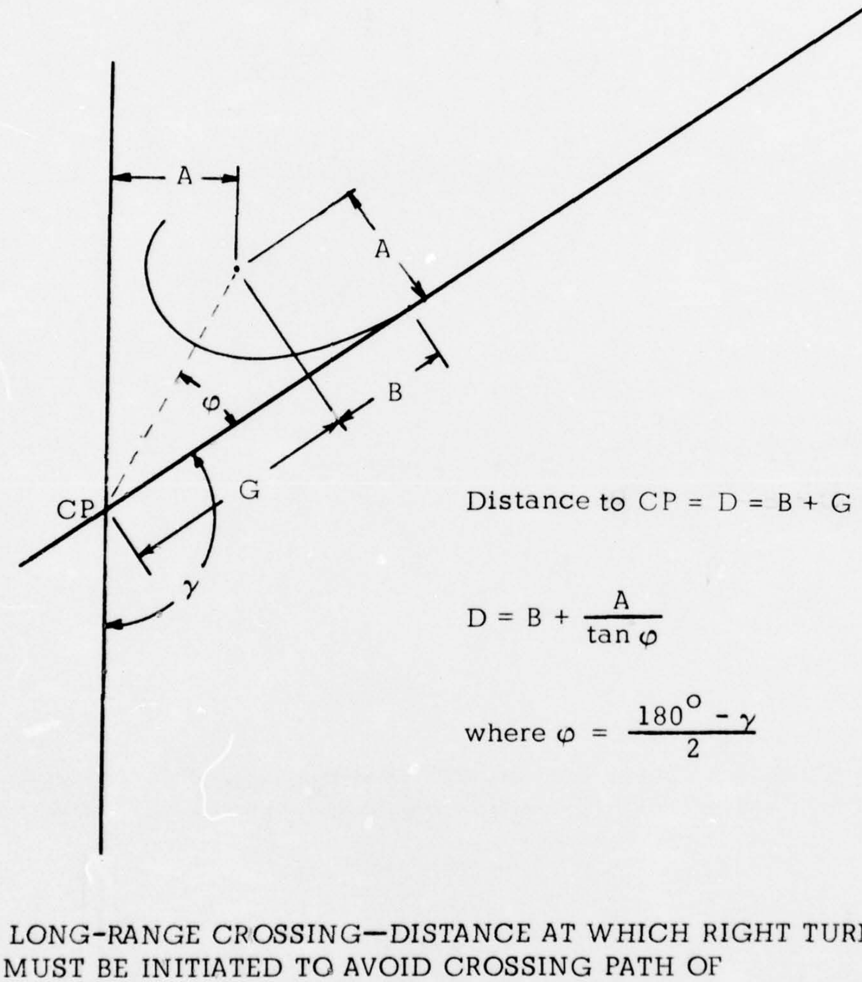
$$TCPA = \frac{D}{v_2} . \tag{2.30}$$

For the second case, in which Vessel 2 passes safely astern of Vessel 1, a computerized numerical procedure is employed similar to the one used in computing CR for the meeting case.

In the analysis set up in the maneuver model the assumption is made that whatever the response of Vessel 2, he will end up trying to either (1) pass astern of Vessel 1 or (2) avoid crossing the path of Vessel 1. Thus, as the courses of the two vessels become closer to being reciprocal it is more difficult for the right turn maneuver to yield either result. In nearly head-on cases, if Vessel 2 were to turn to starboard he would likely pass ahead of Vessel 1. The left turn response as well as the deceleration response, on the other hand, does not lead to this problem. Both would always result in passing astern of the give-way vessel, as long as the action were taken in a timely fashion.

<u>Sudden Appearance Scenario</u>

The sudden appearance scenario uses essentially the same modeling approach as the long-range crossing. As stated earlier, the questions being asked here are the only differentiating feature. For any given crossing situation, it is desired to know how long before the collision there must be an awareness of the threat and action initiated in order to avoid collision. For a smaller, more maneuverable (or more controllable) vessel, less time and distance is required than for a larger one. The question is: with a given maneuverability and set of scenario parameter values, <u>how early</u> does evasive action <u>need</u> to be initiated?



Distance to CP = D = B + G

$$D = B + \frac{A}{\tan\varphi}$$

$$\text{where } \varphi = \frac{180^{\circ} - \gamma}{2}$$

FIGURE 7. LONG-RANGE CROSSING—DISTANCE AT WHICH RIGHT TURN MUST BE INITIATED TO AVOID CROSSING PATH OF GIVE-WAY VESSEL

Head-On Scenario

The head-on scenario, as depicted in Figure 8, models two vessels having reciprocal headings on the same track. The question here is at what range must Vessel 2 turn in order to miss Vessel 1 with an acceptable safety margin? (Safety margin is input in place of the width of Vessel 1 in the computer program.) Vessel 1 is assumed either not to maneuver or to maneuver away from own ship's maneuver direction. The output information obtained from this model is (1) the range between the two vessels at which Vessel 2 must initiate the turn response, and (2) the time it would normally take to close this range to 0 if no turn was made--TCPA (time to closest point of approach where CPA = 0).

ENERGY EXCHANGE SUBMODEL

The energy exchange submodel accepts input from the parallel scenario submodel and computes the energy, E_d, available for deforming the struck vessel's hull. The methodology is a straightforward application of Newtonian mechanics and the approach applies to all collision scenarios although computations in the computer model are made only for the parallel scenarios in which total collision prevention is not assumed as in the long range crossing. The basic assumption employed in this methodology is that the collision is inelastic; that is, the two vessels stick together following the collision and the striking vessel does not absorb any of the energy dissipated in deforming the other vessel's structure. This assumption is conservative in that some collisions occur in which both vessels suffer appreciable structural damage.

Given the velocities of the vessels at collision, the position where the struck vessel is hit, and the angle at which it is hit, the energy dissipation may be computed. In the inelastic collision of two vessels, energy is spent on (1) changing the linear velocity vector of each vessel, (2) causing the two vessels to rotate about their own axes (both assumed to have no rotation before collision), and (3) deforming the structure of the struck vessel. Since conservation of momentum must take place and both vessels must be stuck together after collision, it is possible to calculate the new linear and rotational velocity vectors from their momentum equations. Then, the new linear and rotational energy may be calculated. By using the total linear motion energy before collision and subtracting the total linear and rotational energy of the two vessels after collision, the difference will be the energy used in the destructive process of hull plate and structural deformation, E_d. Or,

$$E_d = E_{Total} - \left(E_{Rotate} + E_{Linear}\right). \tag{2.31}$$

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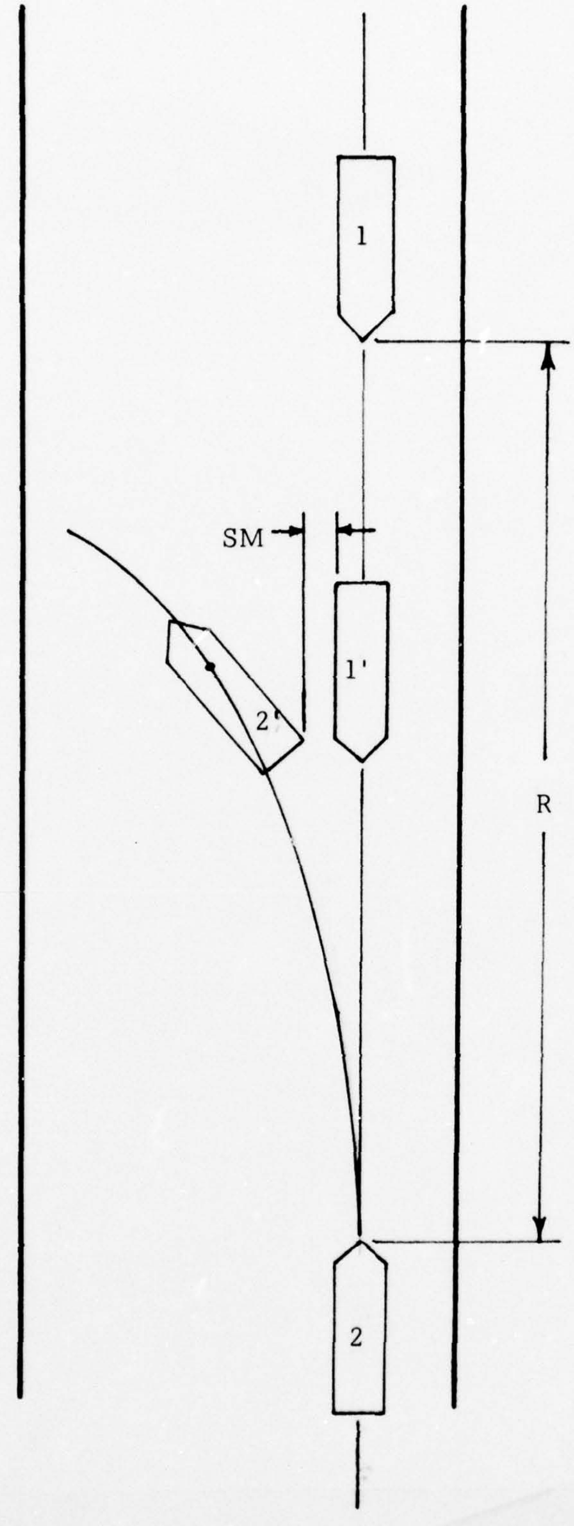

FIGURE 8. HEAD-ON SCENARIO—RANGE AT WHICH TURN MUST BE INITIATED

The total energy in the collision is given simply by Equation (2.32)

$$E_{Total} = (m_1 v_1^2 + m_2 v_2^2)/2 \qquad (2.32)$$

where

m_i = The mass of the i^{th} vessel

v_i = The velocity of the i^{th} vessel before collision.

$$E_{Rotate} = (I_1 \omega_1^2 + I_2 \omega_2^2)/2 \qquad (2.33)$$

where

ω_i = The angular velocity of the i^{th} vessel after collision

I_i = The mass moment of inertia of the i^{th} vessel.

The final linear energy of the vessel is given by Equation (2.34)

$$E_{Linear} = (m_1' u_1^2 + m_2' u_2^2)/2 \qquad (2.34)$$

where

m_i' = The effective mass of the i^{th} vessel (including entrained water)

u_i' = The steady-state linear velocity of the i^{th} vessel after collision.

The derivation of these equations is based on a paper by J. H. Haywood.[2/] A more detailed treatment is contained in Appendix H.

HULL RUPTURE SUBMODEL

Once the collision energy is known, further analysis can be conducted to determine the consequences. In the case of an oil tanker, all that is required for a spill is rupture of its hull plate. However, it is extremely difficult to determine from the collision energy data alone whether or not a spill will result. Such factors as position of strike relative to the web-frame structure (i.e., did

2/ Haywood, J. H., Ship Collisions at Varying Angles of Incidence, NCRE/N 163, Naval Construction Research Establishment, United Kingdom, 1954.

strike occur on or near a web-frame or was it halfway between), location of weld seams, thickness of hull plate, strain properties of steel plate, the shape of the striking ship's bow, etc. enter into the formula for determining rupture or nonrupture. In lieu of definitive evidence and a widely accepted model of this process, the hull rupture submodel in this research uses an input strain energy value, E_s. A comparison of deformation energy, E_d, is made to E_s and if $E_d \geq E_s$, rupture is said to occur.

In the computer analysis, a collision region for a given scenario and response is calculated. Then N points are selected at uniform intervals in the front and rear portions of the collision region and collision energy, E_d, is computed for each point. For example, the front portion of the collision region is defined as the region in which the vessel there will be struck. So, for the N collisions a test is made to see how many have energy E_d which exceed the vessel's strain absorption capability, E_s. Since it is assumed that the location of the vessels in the channel is a random variable with uniform distribution the same must be true of any section of the channel—in particular the collision region. Consequently, N points in the front and in the rear portions of the collision region are selected at uniform intervals. Thus, the probability of rupture given that the vessel is in the region is

$$P(R \mid \text{vessel is in region}) = \frac{N_R}{N} \tag{2.35}$$

where N_R is the number of times $E_d \geq E_s$ for N points (collisions).

This model does not consider the way in which energy is dissipated in hull deformation over a given time period. The crucial link in actually determining hull rupture is knowledge about the <u>instantaneous force</u> which is exerted on the hull plate at any time (but particularly at time = t_{max}) and the local strain to failure. Figure 9 illustrates the time history of force for two inelastic collisions. The one taking place in time t' is more inelastic, or rigid than the one occurring over time t. The times required, t and t', are for the vessels to collide, exchange energy, and achieve a steady state. For smaller times, instantaneous maximum force becomes greater. For a longer time in the dynamic process of collision, the maximum force will be less and the impact energy will be more evenly distributed over time. In addition to this, one must consider maximum pressure on the hull plate. With different striking surfaces the force at any point in time may be more or less evenly distributed over the surface area of the struck vessel to give more or less local pressure.

In any case, the model presented in this report takes advantage of collision energy in two ways. First, a strain energy to rupture may be selected and integrated with the collision probability analysis to yield probability of rupture, given an exposure opportunity. In the second approach, two types of output may be produced. The first is the collision probability information, and the second is average and maximum expected collision energy information.

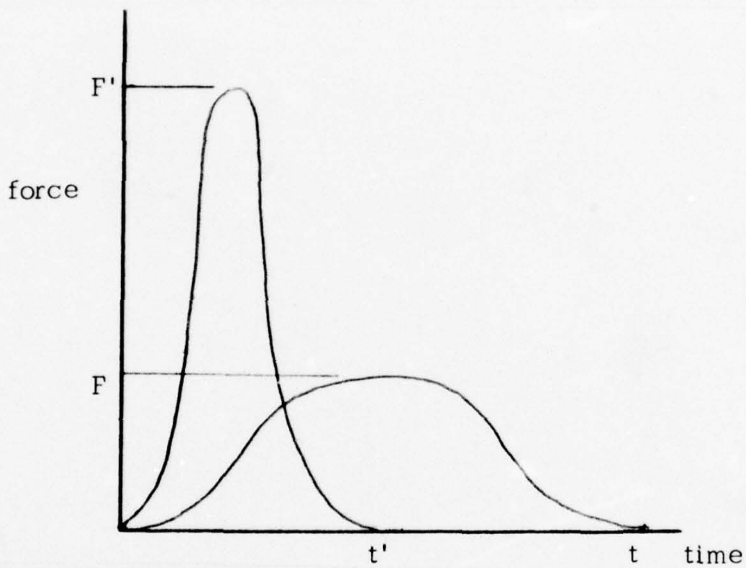

FIGURE 9. TIME HISTORY OF FORCE FOR TWO INELASTIC COLLISIONS

In the latter case changes in one or more of the system variables would yield information on both the likelihood and severity of collision, without actually estimating whether or not there will be a rupture.

SYSTEM PARAMETERS

Now that the basic nature of the model has been presented, discussion will proceed to the three classes of system parameters which were shown in Figure 2. Table 1 is a list of all the system input parameters. It should be noted that not all parameters are used for each scenario. The vessel and scenario parameters are fairly straightforward and require a minimum of description. The parameters dealing with vessel controllability and response to collision, on the other hand, are more involved and are dealt with in detail in the following portion of this section.

Turning and changing speed are at the focal point of the entire analysis in this report. Whenever sensitivity is conducted on one of the system parameters the usual effect is to change the amount of time available for the maneuvering vessel to avoid collision. A greater track separation, more maneuverability, quicker human and engineering responses, less initial speed, etc. all lead to more time for responding. Consequently, the need for a reasonable model of the turning and speed changing phenomena is paramount. The model presented in this section, while original in form, is based upon empirical results of C. Lincoln Crane, Jr. [3/]

Vessel Parameters

The vessel parameters describe the relevant physical characteristics of the two ships being modeled. The first three (length, width, and weight) generally describe the size of each vessel. The next two (pivot point and crab angle) describe basic turning characteristics which would not be expected to vary significantly for a wide variety of vessels and, hence, not set up for sensitivity analysis. The last parameter is the strain energy to hull rupture, E_s. This value is used as if it were uniform for every point along the side of the vessels. In the previous section on hull rupture it was said that it is very difficult to determine E_s for any given collision situation. Thus, one value is picked (which conservatively, could be a minimum value). Although the approach may be crude, a substantially better alternative is not immedicately available.

Response Parameters and Vessel Controllability

The maneuver analysis deals with two basic scenario situations. First, there are the restricted waters scenarios—parallel meeting and the parallel

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[3/] Crane, C. Lincoln, Jr., Maneuvering Safety of Large Tankers: Stopping, Turning, and Speed Selection, Annual Meeting of the Society of Naval Architects and Marine Engineers, New York, November 15-17, 1973.

TABLE 1

PARAMETERS USED IN MODEL

System Parameters	Parallel	Long-Range Crossing	Appearance	Head-On
Vessel				
1. Lengths, feet (L)	X	X	X	X
2. Widths, fraction of length*	X	X	X	X
3. Weight, gross tonnage (long tons)	X	X		
4. Crabbing angle, degrees*	X	X	X	X
5. Pivot point, fraction of length from bow*	X	X	X	X
6. Strain energies to rupture hulls (E_s)	X			
Response				
1. Engine order—1, 2, ..., 6** (R_{EO})	X	X	X	
2. Turn order—1, 2, 3**(R_{TO})	X	X	X	X
3. Deceleration, feet/seconds²	X	X	X	
4. Acceleration, feet/seconds²	X			
5. Response time lag to reach 85% of full acceleration/deceleration (Alpha 2)	X	X	X	
6. Final (steady-state) turning radii, feet (R)	X	X	X	X
7. Ratio of transfer to steady-turning radius (A:R)*	X	X	X	X
8. Response delay, fraction of track separation (Alpha 1)	X			
Scenario				
1. Which scenario*	X	X	X	X
2. Initial velocities (V)	X	X	X	X
3. Initial relative courses (γ)		X	X	
4. Track separation (S)	X			

* Not explicitly set up in computer model for sensitivity analysis.
** See Table 2.

overtaking. Second, we have the long-range crossing scenario or the open waters case. The analysis in the two categories is handled with some commonality, but there are many differences.

In a restricted waterway, a vessel often encounters threatening, or dangerous circumstances from being forced into close proximity with other vessels. Hence, the analysis is geared to point out ways to reduce likelihood of collision. The open water, long-range crossing scenario, on the other hand, is somewhat different. Our response to the threat situation now is not directed toward a reduction in probability of collision, but in eliminating the collision altogether.

In the maneuver model the various possible responses of turning, (R_{TO}) and changing speed, (R_{EO}) may be used either independently or together. (See Table 2.) The nature of the model is such that the response is expressed in terms of the physical forces, i.e., only resultant effects are modeled. For instance, when deceleration is used it is expressed in terms of feet/second^2. The actual command is a "full astern" order which has inherent certain time delays in initiation and other processes which take place that eventually result in a deceleration measurable in feet/second^2. Our model, however, approximates the real slowing process by using a function of accelerative force over time as follows:

- After the engine order is given, there is a delay during which no accelerative force exists.
- After the delay, the accelerative effect builds up to a steady-state amount in an exponential manner.

The input parameter $Alpha_2$ is a measure of how long this process takes. It is the number of seconds required to reach 85 percent of the final full effect. (See Figure 10.)

In the same context, the turning response in this model is approximated by a spiral which has a variable length tail and final turning radius. It is clear, again, that the actual order is in terms of a rudder angle and that the path of the ships is then a matter of hydrodynamics. Using the empirical evidence of the C. Lincoln Crane article [4], though, a general functional expression was developed to fit his data, both in terms of the turn path as well as deceleration while turning.

Parallel Meeting and Overtaking Scenarios. The basic nature of the parallel meeting (or overtaking) scenario, as discussed previously in this section, is of two ships meeting in a channel. One of them may, for any reason, initiate a turn which endangers the other. The other ship perceives

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4/ Ibid.

TABLE 2

RESPONSE MANEUVER

R_{EO} / R_{TO}	No Engine Order 1	Appropriate Deceleration 2	Appropriate Acceleration 3	Appropriate Use of Both 4	Blind Deceleration 5	Blind Acceleration 6
1. No turn		*				
2. Left turn		*				
3. Right turn	**	*	**			**

* R_{EO} response used in sensitivity analysis for this report with R_{TO} = 1, 2, 3.

** Right turn for these R_{TO}'s result in a collision situation very far off the course track of the responding vessel. Hence, the channel width constraint would preclude playing out the scenario.

Note: "Appropriate" means than an engine order is not made, if the result is moving into the collision region from an otherwise safe position. "Blind" on the other hand allows for collisions being caused by the response; no regard is given to being in or out of the "No Change" collision region.

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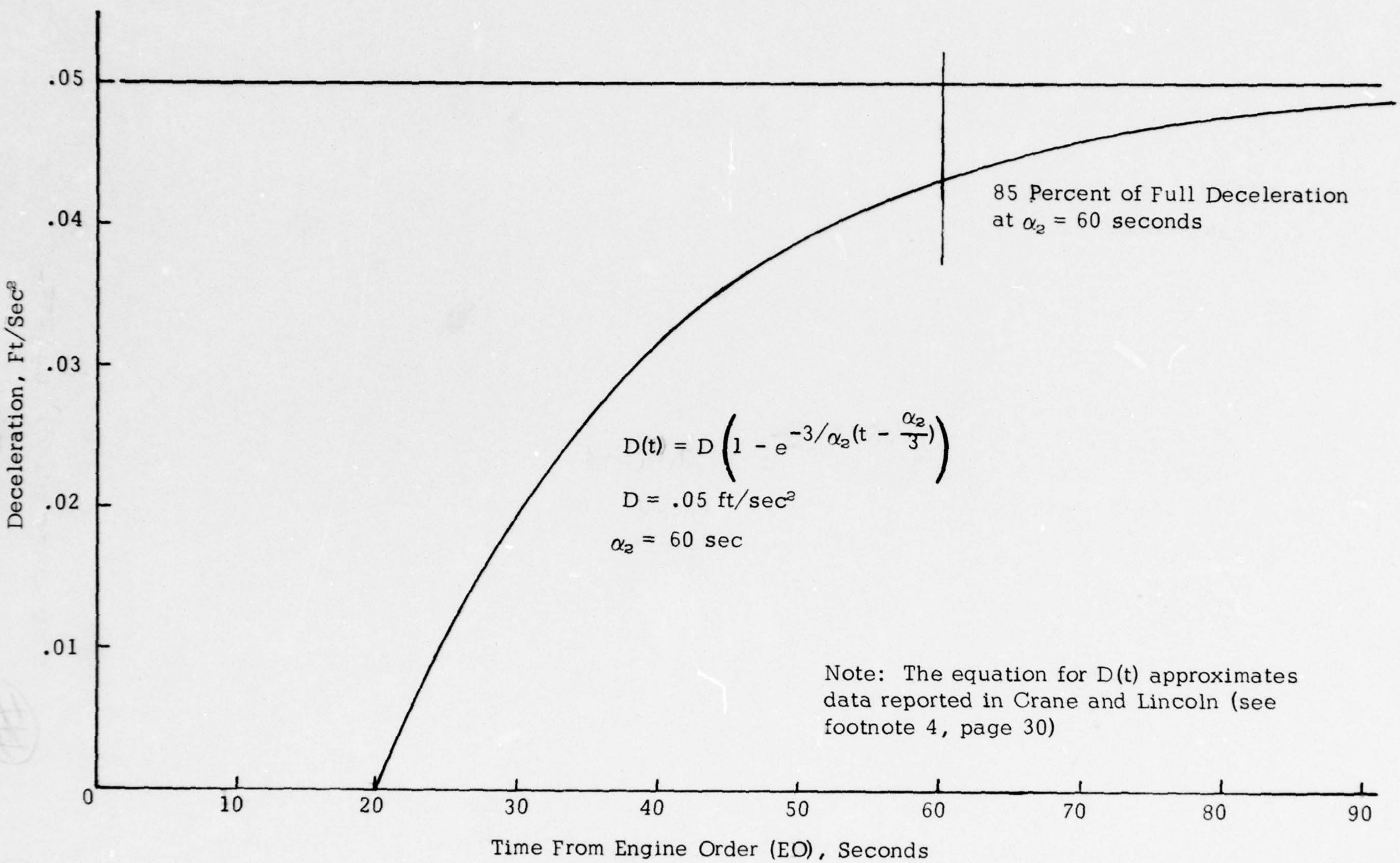

FIGURE 10. EXPONENTIAL DECELERATION WITH TIME LAG

the turn at a specified instant and responds in a manner which will hopefully minimize the probability of collision and/or severity of that potential collision. The response occurs when the first ship is observed in a turn and has reduced the normal track separation between the two vessels by a certain percentage (20 percent in the base case). This response delay is called the α_1 parameter. The collision-avoidance response order is then given—a turn and/or speed change is begun. In the turn case, the model incorporates the assumption that the order is rapidly carried out and that the ship begins a turn along a spiral path. In the case of an engine order, the action is somewhat more complicated in that an additional time delay, the α_2 parameter, is involved and full propulsion power in response to the order is built up over a period of time. In addition, there is an option of both turning and changing speed simultaneously.

Long-Range Crossing, Head-On and Sudden Appearance. In these cases, the focus of the analysis is slightly different, since the goal is to determine the conditions for reducing probability of collision to zero. The analysis yields the conditions for collision avoidance with each type of response.

The Engine Order Response. As discussed above, the applied acceleration response (either positive or negative) which is modeled in this analysis is a simplified approximation of true behavior in a vessel speed change. In the Crane article [5], the 27,000 DWT Esso Suez, which is used in this report for baseline case purposes, requires about 60 seconds to establish full reverse thrust. In Figure 11 it may be seen that at the end of 60 seconds, 85 percent of full deceleration capability is achieved. Figure 11 illustrates the difference in effect on velocity over time when time delay and exponential build-up is used in place of an instantaneous deceleration. For an initial velocity of eight knots, an increase of greater than 36 seconds is observed in the time required to stop the ship.

An important consideration in the process of deceleration is that it is possible to develop a negative velocity. Naturally, the hydrodynamics of accelerating in reverse are different than accelerating ahead. If care is not taken in the development of the collision region model, dubious as well as incorrect answers may result in which one ship is backing down at high speed. For instance, consider the condition for the rear boundary of the collision region. At this point the condition for collision is that the responding ship's bow strikes the stern of the turning ship. If the responding ship has sternway the situation is illogical. (At the instant before collision the decelerating ship would have had to be forward of his present position, or he would have been lying across the turning ship—an impossible scenario.) Thus, in the

[5] Ibid.

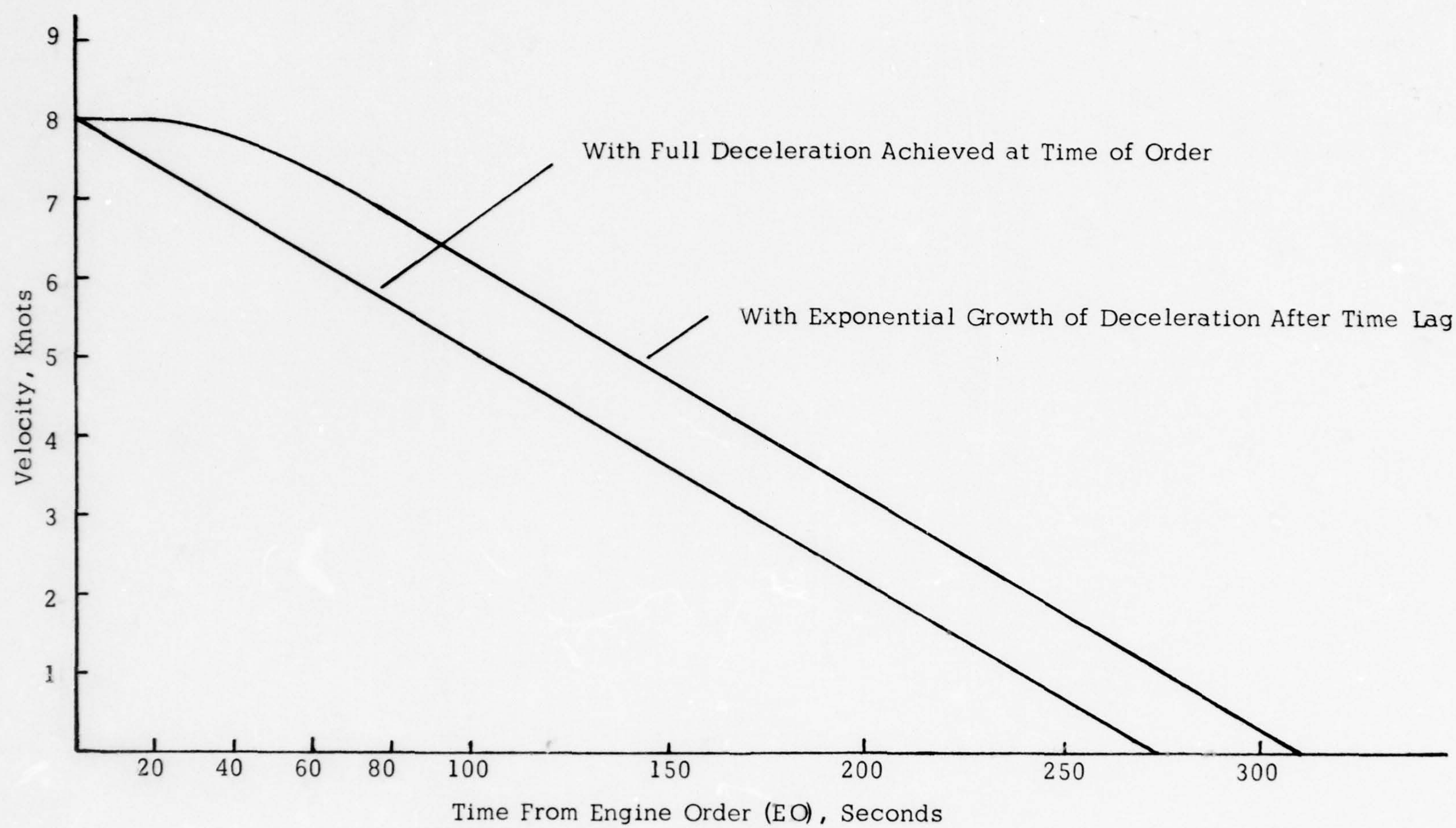

FIGURE 11. COMPARISON OF VELOCITY OVER TIME, v(t), FOR INSTANTANEOUS AND DELAYED DECELERATION

computation to determine the rear boundary of the collision region, the striking ship must have a nonnegative velocity. On the other hand, the center divider and front boundary of the collision region describe a collision limit in which it is possible to have sternway when hit by the turning ship. For the purposes of analysis reported here, the slowing ship develops a maximum reverse velocity of four knots. If this limit were not set it would be feasible to produce solutions having a velocity as high as 20 to 30 knots astern.

The Spiral Turn. Following an examination of the results from the empirical trials conducted by Crane, there arose concern about the accuracy of using circular turns in the model. Crane's evidence pointed out that a circular approximation for the path of a turning ship is dubious at best. A search was commenced for a more accurate means of representing the path of a ship in a turn.

A primary objective was that the description of the turn would have as few parameters as possible yet still would be representative of the turn phenomena. Since the circular turn was inadequate the next step was to go to a function describing a locus of points very similar to a circle but more general. Hence, the spiral curve was selected. The equation used to model the spiral turn is

$$R(\theta) = R(1 + Ce^{-H\theta}) \tag{2.36}$$

where

$$C = \frac{\sqrt{A^2 + B^2}}{R} - 1$$

and

$$H = \frac{B(C+1)}{AC}$$

A = Transfer

B = Advance less steady-turn radius

R = Final turn radius.

Note: The spiral parameters C and H are aggregations of A, B, and R determined by the conditions that the spiral tail is tangent to the original course of the vessel at the commencement of the turn.

The parameters A, B, and R are shown in Figure 12. A is the distance from the original, straight-line path of the ship to the center of its turning circle. B is a measure of the length of the spiral tail—the distance from the initiation of turn to the center of the turning circle as measured along the original path line. Finally, R is the radius of the turn after a steady-state condition is reached and a turning circle is established. The ratio A:R, is a measure of how quickly and tightly the spiral wraps around the final, or steady-state,

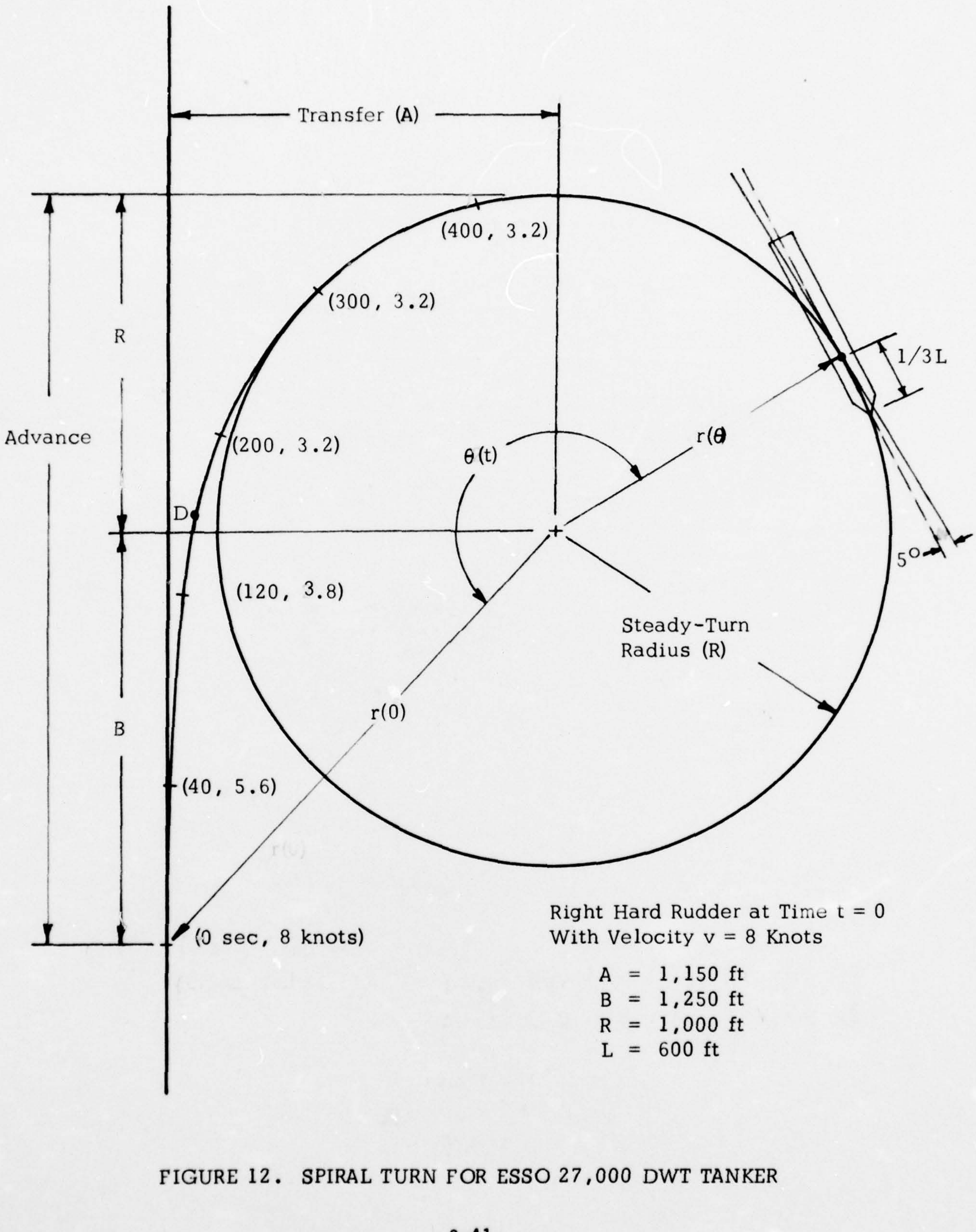

FIGURE 12. SPIRAL TURN FOR ESSO 27,000 DWT TANKER

turning circle. A ratio of 1:1 indicates a very tight wrapping and a ratio of 2:1, for example, is a loose wrapping.

The position of the ship at any time during the turn is specified by its polar coordinates θ and $r(\theta)$ where θ is measured from the vector $r(0)$ the start of the turn (see Figure 13). As the angle θ increases, $r(\theta)$ approaches R and the exponential portion of Equation (2.36) becomes negligible.

The second major consideration in turning, once the description of the path is made, is the "drag deceleration." According to the tests run by Crane, a large tanker experiences significant deceleration in a turn. He illustrates, in two trials of a 191,000 DWT tanker, that the ratio of initial to final velocity is approximately 3.33:1, for initial velocities of 16 and 6 knots. He also indicates that the majority of this deceleration occurs during the initial part of the turn and that after the ship has turned about 90° the velocity changes little. When using Equation (2.36) for modeling the turn, assuming the angular velocity $d\theta/dt$ to be a constant,* and using the dimension of the spiral base on the illustrations in the Crane article, linear velocity ds/dt decreases in a manner such that after turning about 90° velocity changes little, and, in fact, has reduced by approximately the ratio which was empirically derived. Figures 13 and 14 illustrates the magnitude and timing of the deceleration based upon this model of turning for our base case example. The greatest deceleration occurs early and drops off to near zero as the ship progresses into the turn. The strength of the deceleration effect is expressed by the ratio

$$\frac{v_i}{v_f} = \frac{A^2 + B^2}{AR} \qquad (2.37)$$

given A, B, and R as defined in Figure 13. From the Crane diagram of the 191,000 DWT ship executing a right turn with maximum rudder, A, B, and R were measured to be:

A = 1,500 ft

B = 2,000 ft

C = 1,300 ft.

Using these values the ratio of initial to final velocity is 3.21:1—very close to the ratio 3.33:1. Figures 14, 15, and 16, however, illustrate the parameter values of the ship which will be used as a "base case" in the next section for sensitivity analysis. The values of the spiral turn parameters for this case are:

A = 1,150 ft

B = 1,250 ft

C = 1,000 ft.

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*This assumption leads to a good approximation of Crane's empirical results.

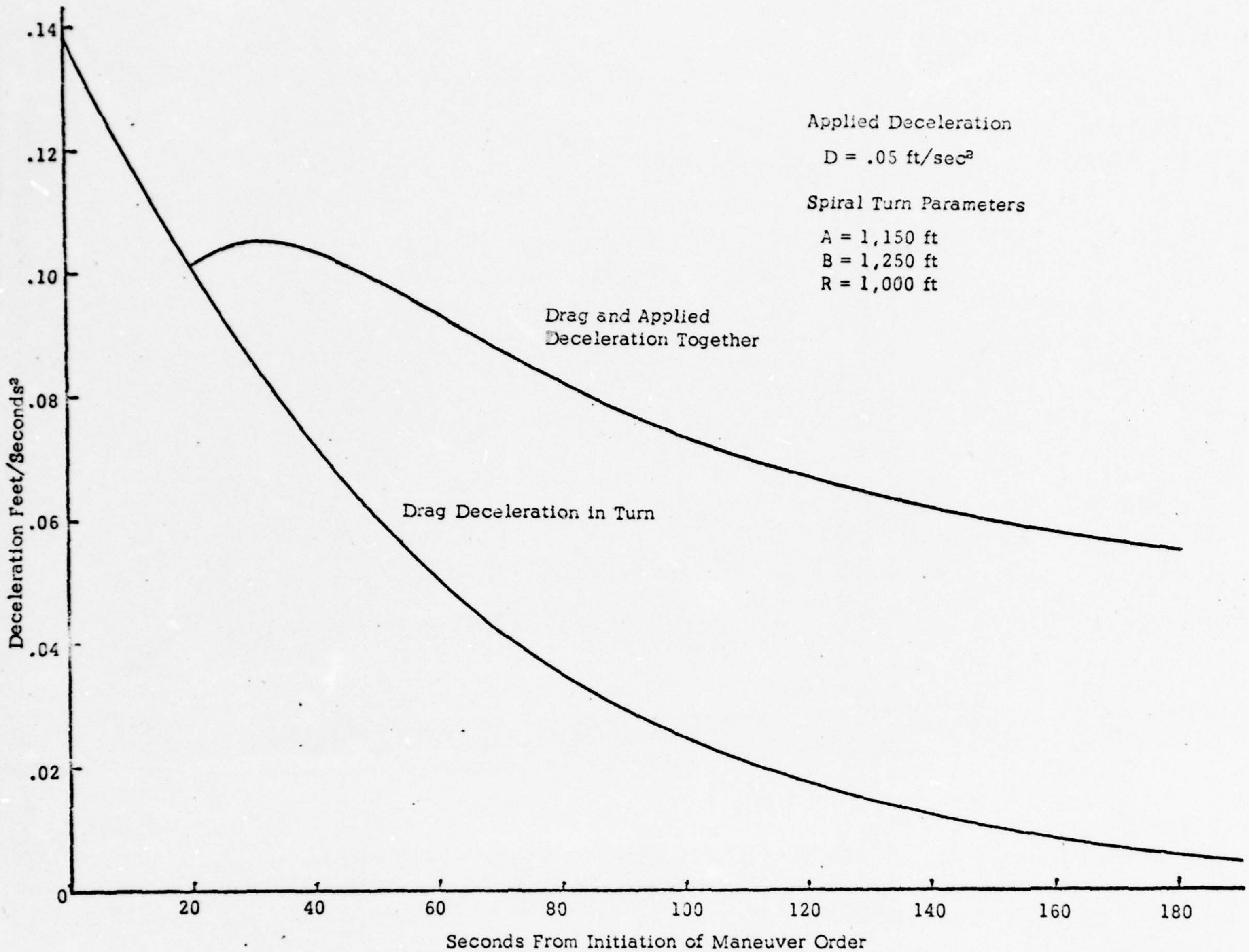

FIGURE 13. DECELERATION IN A SPIRAL TURN—WITH AND WITHOUT APPLIED DECELERATION FROM AN ENGINE ORDER

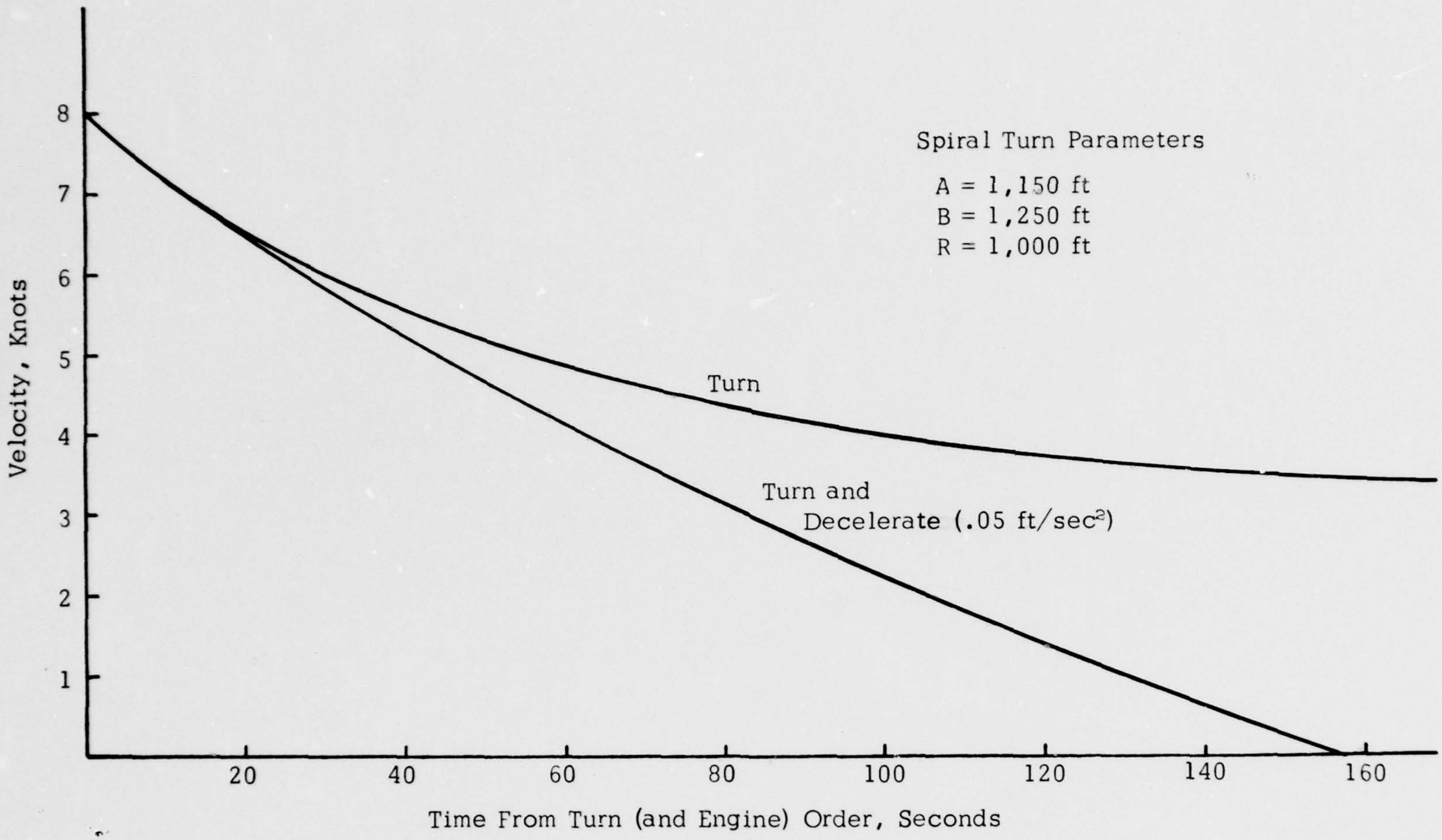

FIGURE 14. VELOCITY OVER TIME FOR A SPIRAL TURN—WITH AND WITHOUT APPLIED DECELERATION FROM AN ENGINE ORDER

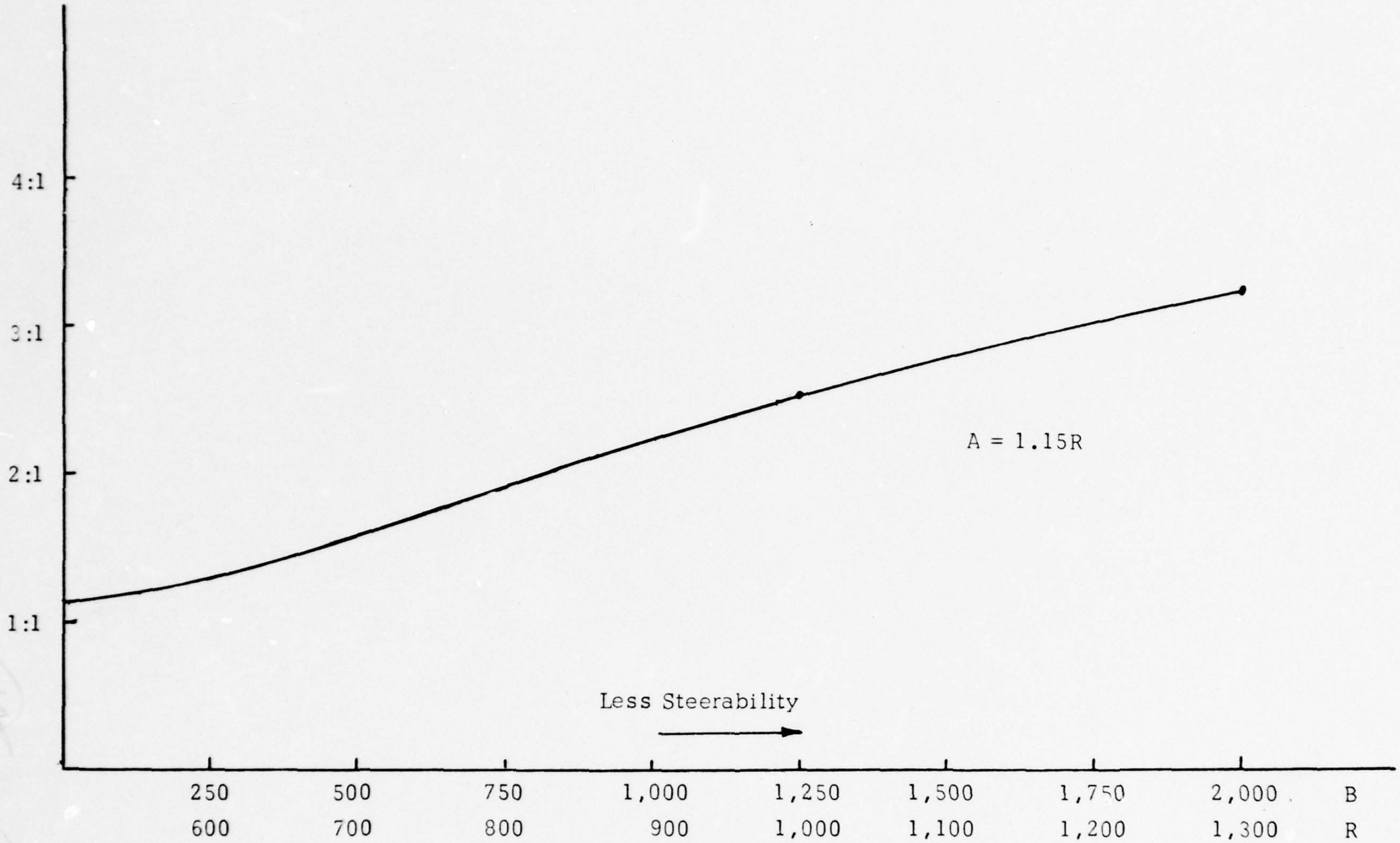

FIGURE 15. RATIO OF INITIAL TO FINAL VELOCITY FOR COMBINATIONS OF PARAMETER B AND R IN SPIRAL TURN

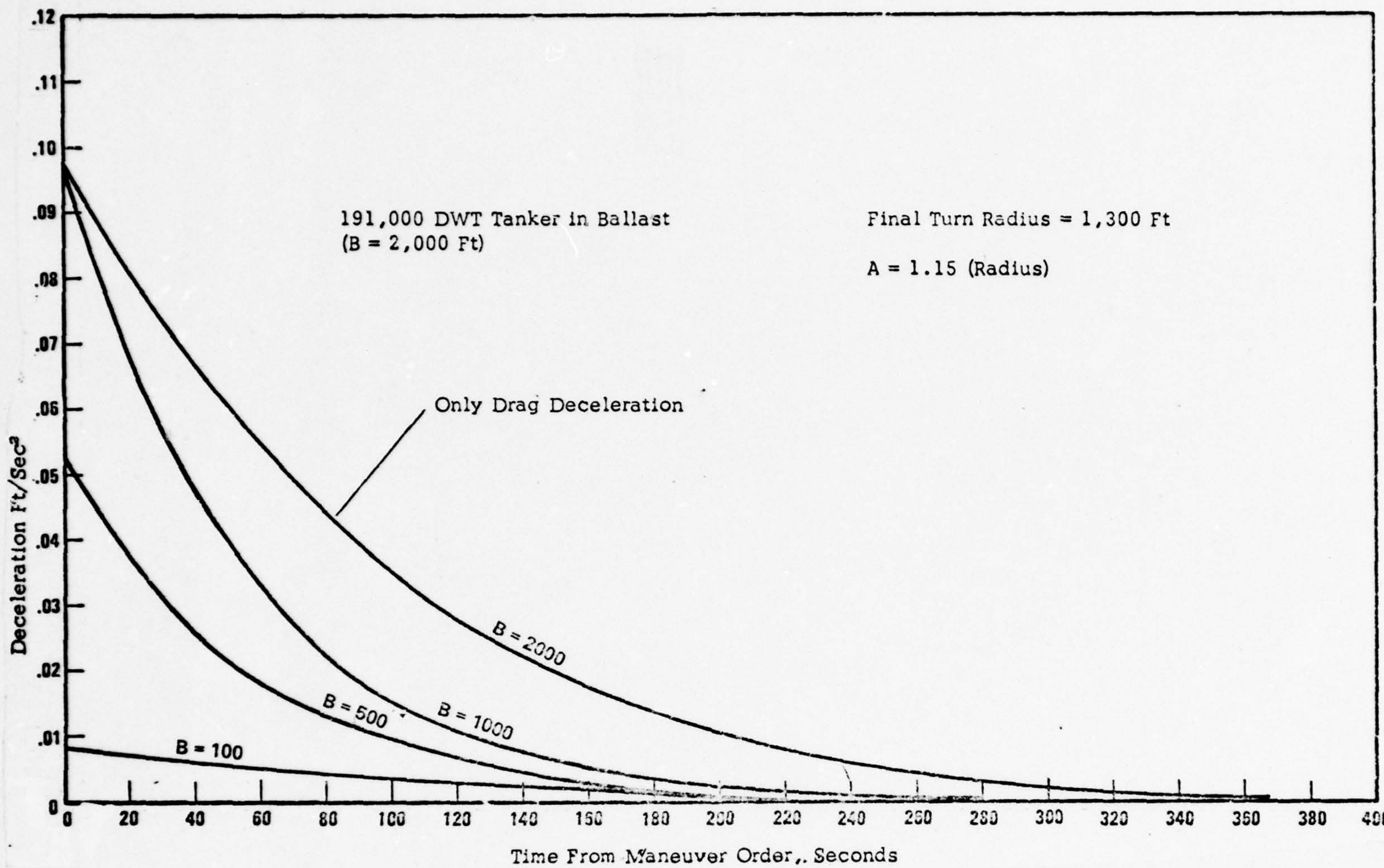

FIGURE 16. TURN DECELERATION OVER TIME FOR VARIOUS VALUES OF SPIRAL TAIL LENGTH—FOR B = 2,000 DECELERATION IS FOR 191,000 DWT TANKER IN BALLAST

Using these values the ratio of initial to final velocity is now 2.5:1. Or, if this vessel were to turn, with an initial velocity of eight knots the velocity after making a 90^{o} turn would be 3.2 knots.

An increase in B or A, or a decrease in R will give a greater decelerative effect during the turn. If values of the parameters were chosen such that B = 0 and A = R, then Equation (2.36) would reduce to $r(\theta) = R$. Or, with these parameter values the turn would be circular and the ratio of initial to final velocity would be 1:1.

For the purposes of the analysis in this report, A is defined to be directly proportional to R, or A = aR. Making this substitution into Equation (2.37):

$$\text{Velocity Ratio} = \frac{v_i}{v_f} = \frac{a^2R^2 + B^2}{aRR} \qquad (2.38)$$

where a is usually slightly greater than 1, and

$$\frac{v_i}{v_f} = a + \frac{1}{a}\left(\frac{B}{R}\right)^2. \qquad (2.39)$$

Then, as $B \Rightarrow 0$, the Ratio $\rightarrow$ a. Also, as B increases so does the ratio, and hence the deceleration effect. Figure 15 illustrates the ratio for several combinations of B and R. Figure 16 shows the time history of deceleration for different values of B and fixed A and R.

The deceleration described above is the normal consequence of the hydrodynamic effects encountered in a turn, with a constant rudder angle and no change in engine orders. Using Equation (2.36), along with the assumption of constant angular velocity ($d\theta/dt = C$), results in a good approximation of the empirical results of the turn trials with a 191,000 DWT tanker in ballast by Crane. It must be realized that with a single screw vessel such as a tanker, torque forces mean that left and right turns are not the same. However, for the purposes of analysis in this model left and right turning are considered similar. The deceleration effect, also, could be handled differently if desired. The simple assumption of this model could be changed to incorporate a more complex function of the type ship involved, time or distance from initiation of turn order, etc. That is, instead of $v = ds/dt$ being a consequence of the choice of A, B, and R and assuming $d\theta/dt$ = const, ds/dt may be described in any way desired and incorporated in the program subroutine dealing with spiral turns.

Also, the model uses the assumption that maneuverability is not affected by initial velocity. Clearly, for low speeds a loss of steering will occur. However, the Crane results indicate that for the range of 6 to 16 knots there was no significant difference in maneuverability. The tanker in ballast which he used in his trials followed approximately the same track at all speeds in this range. The turn radius and spiral tail length were quite similar—virtually the same. In addition, the ratio of initial to final velocity was also very nearly identical.

When a ship turns it is assumed to have a specific pivot point which is specified as a point some fraction of the ship length from the bow. This point is the same for left and right turn and is assumed to be a constant throughout the turn. In addition the vessel has an angle of attack in the turn, a "crabbing angle," as illustrated in Figure 12 by the ship drawn on the lower portion of the turning circle. It is also assumed that this crabbing angle remains constant during the turn and is the same for both left and right turns. Equation (2.31), then, defines the locus of the positions of the pivot point of the ship. Figure 12, which shows the path of the ship in a spiral turn, is actually the path of the pivot point of that ship.

Applied Deceleration in a Turn. In the discussion of turning above, deceleration (drag deceleration), is a transient phenomena—a result of hydrodynamic forces slowing the ship in a turn. However, let us consider the case in which an additional force is applied. In other words, both a rudder and an engine order are given at the same time. The applied deceleration described earlier, a result of a command to the engine room, is added to the drag deceleration. Figures 13 and 14 illustrate the net effect of this summation. In Figure 12, then, point D is the position in the turn at which the ship would come to a full stop if applied deceleration were used. (It should be noted that the ship at point D is very close to its original course path!)

Scenario Parameters

The third class of system parameters are those which specify the nature of the two ship interaction. In short these parameters specify the way in which two vessels engage each other such that emergency maneuvering is necessary in order to avoid collision.

First, it is necessary to specify which of the five cases one wants to model. With the suitable choice of input values any two-ship interaction, in which secondary "gaming type" responses are not a factor, may be modeled: parallel meeting, parallel overtaking, long-range crossing, head-on, or sudden appearance scenario. Second, the initial velocities are set. Finally the relative courses are specified. For the restricted water scenarios—parallel and head-on the courses are set to be reciprocal. However, for the unrestricted waters scenarios—long-range crossing and sudden appearance—the angle at which the vessel paths intersect is also an input parameter and must be selected.

Model Output for the Parallel Scenarios

Figure 2 showed that for the parallel scenarios there are two ways of calculating output information. First, one may wish to utilize a strain energy, E_s, in calculating probability of rupture sensitivity. In this case the output for any parameter change is the percentage increase or decrease in the expected number of collisions resulting in rupture. Second, instead of combining P(C|E) and P(R|C) together for the P(R|E) one may elect to analyze the two separately. In this case the expected percentage change in number of collisions is given along with the average and maximum expected energies. With the energy information the analyst is offered independent measures of severity of collision and likelihood of collision.

This latter format may be particularly useful in view of the fact that there are great difficulties in determining the hull rupture likelihood. Many variables enter into such a calculation and render such an analysis a vastly complex affair. Hence, two types of output are presented and the analyst chooses the one which suits his purposes best.

Also, for the parallel scenarios, it is necessary to choose a subset of the total scenario which is of interest. That is, one may be interested first with the total spill-risk problem in which either of the two vessels may commit the turn error and either may be struck. However, if one of the vessels is a tanker with a hazardous cargo and the other is an empty freighter, then a subset of the scenario may be more of interest. In this case we look at the situation in which either vessel commits the error, but we are now only evaluating the likelihood of the tanker being the struck vessel and performing sensitivity in order to see what reduces that chance.

In all, there are nine subsets of the parallel scenario for which sensitivity may be conducted (see Table 3). For different vessels and different controllability characteristics the results of a change in value of each system parameter may give different answers for each subset being analyzed. That is, a parameter change could increase the probability of Ship 1 being hit and decrease the probability of Ship 2 being hit. Table 3 lists all the possible scenario subsets. The sensitivity indicates an increase or decrease in the probability of collision (or hull rupture) for whichever scenario subset is used.

Having the nine subsets of the scenario may be very useful. For example, in the case described above where one vessel is carrying a polluting cargo and the other is not, a parameter change may result in the overall collision (rupture) probability to decrease. However, this may disguise a very important result which is not being revealed. The probability of the freighter being struck may be reduced considerably and the probability of the tanker being struck (rupture) is only slightly reduced or even increased. Thus, relatively speaking the tanker is not benefitting from the parameter change. If the tanker is Vessel 2, then comparing the result of output Type 2 to output Type 3 would reveal this.

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TABLE 3

CLASSES OF MODEL OUTPUT FOR THE PARALLEL SCENARIOS

1.	Either ship errs, either ship hit
2.	Either ship errs, Ship 2 is hit
3.	Either ship errs, Ship 1 is hit
4.	Ship 1 errs, either ship hit
5.	Ship 2 errs, either ship hit
6.	Ship 1 errs and hits Ship 2
7.	Ship 1 errs and is hit
8.	Ship 2 errs and hits Ship 1
9.	Ship 2 errs and is hit

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Two Comments on Parameter Values

In concluding the discussion about the three types of system input parameters two comments are in order. First, one of the very crucial determinants of the sensitivity analysis is that the values for all the parameters are held constant while one or more of the other variables is varied. If different base case values are selected it is quite apparent that different consequences would result. It must be constantly borne in mind that any sensitivity analysis is good only when the type ships, their maneuver characteristics, the scenario being discussed, and the kind of response are consistent with values of the real situation being studied. For example, when considering the possibility of different channel widths one must use a set of ships which is of interest. The effect of different channel widths depends greatly, obviously, on the type ships passing through the channel. Hence, when any use of the model gives an indication of sensitivity to the channel width constraint, such analysis is for the pair of ships modeled. Further analysis must be conducted to determine robustness of the results for all vessels by using different maneuver characteristics and dimensions.

Second, the modeling of ship maneuvering in extremis becomes very involved and takes much time to look at the many possible conditions and logical anomalies which arise as a consequence of the simulation of such a complex process. There is a good bit of variety in the type of collisions which may occur. Simple assumptions serve for a significant accounting of the many possible combinations of input values. However, the mathematical and geometrical conditions for collision may not serve for all possible cases. For instance, if two very different ships are modeled, it seems apparent that collision region inversion takes place for turning response. That is, the geometric front of the region is the back mathematically and the back is the front. The mathematical condition for collision does not easily tell us which side of the ship is hit when turning. If the responding ship decides to decelerate it is certainly possible to be moving either in reverse or forward when collision takes place and there is a clear distinction in reality between the two cases while the mathematical conditions look identical.

This is all to say that unusual and unexpected results may occur which have not been thoroughly and exhaustively checked out for all possible input values. Care must be taken to ensure that the model user does not use the model in such a way as to get results which may be in reality infeasible or logically inappropriate. As long as markedly different ships in the pair are avoided, the answers yielded will be accurate.

THE SOLUTION PROCESS FOR FINDING THE SIZE OF THE COLLISION REGION

The following discussion is a presentation of the general methodology employed in the scenario submodels of Figure 2. The organization of the relevant computer subroutines is given, and an example is presented to illustrate the way in which the subroutines interact to yield information about the size of the collision region.

The scenario submodel programs for the five scenarios are organized into various groupings of subroutines as follows:

1. COLBOX, STOP, HALT, DECEL, ENEREX, SPIRAL are used for parallel meeting and overtaking scenarios
2. LRC, STOP, SPIRAL are used for the long-range crossing and sudden appearance scenarios
3. HEADON, SPIRAL are used for the head-on scenario.

The subroutine SPIRAL plays a central role in all groupings. Its function is to calculate, for any given time after the beginning of a turn, the position and direction of a vessel as it moves along a spiral. The subroutine DECEL provides similar information for a vessel decelerating along a straight course. The subroutines STOP and HALT are used to determine the stopping position of a vessel when an engine order to decelerate is given, along a spiral turn and a straight course, respectively.

The largest subroutine grouping, COLBOX and its satellites, can be further broken down into three functional sections:

1. Computing size of collision region
2. Computing collision information needed for the energy exchange analysis
3. Energy exchange analysis.

The first two functions are controlled by the COLBOX subroutines, and in the third control passes to the ENEREX subroutine.

In all of the subroutines, the coordinates to be computed occur as roots of transcendental equations. Iteration loops are used extensively to extract their values.[6] As an illustration of the use of Newtonian iteration in the program, we discuss the following example.

EXAMPLE

In this example we describe a parallel meeting with a decelerating response (see Figure 17a). The action begins with the erring ship (ship 1 in the first instance) starting to turn across the path of ship 2. This time is

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[6] Newton's iterative method is the main mathematical tool used in this program. Given a differentiable function f(t), the method allows one to extract a root of f(t) = 0 by the iteration

$$t_{n+1} = t_n - f(t_n)/f'(t_n). \tag{2.40}$$

Usually three loops of iteration give a very accurate value for the root. The solution needed in all cases is the set of points where the rectangle corners representing both Ship #1 and Ship #2 have the same X coordinate.

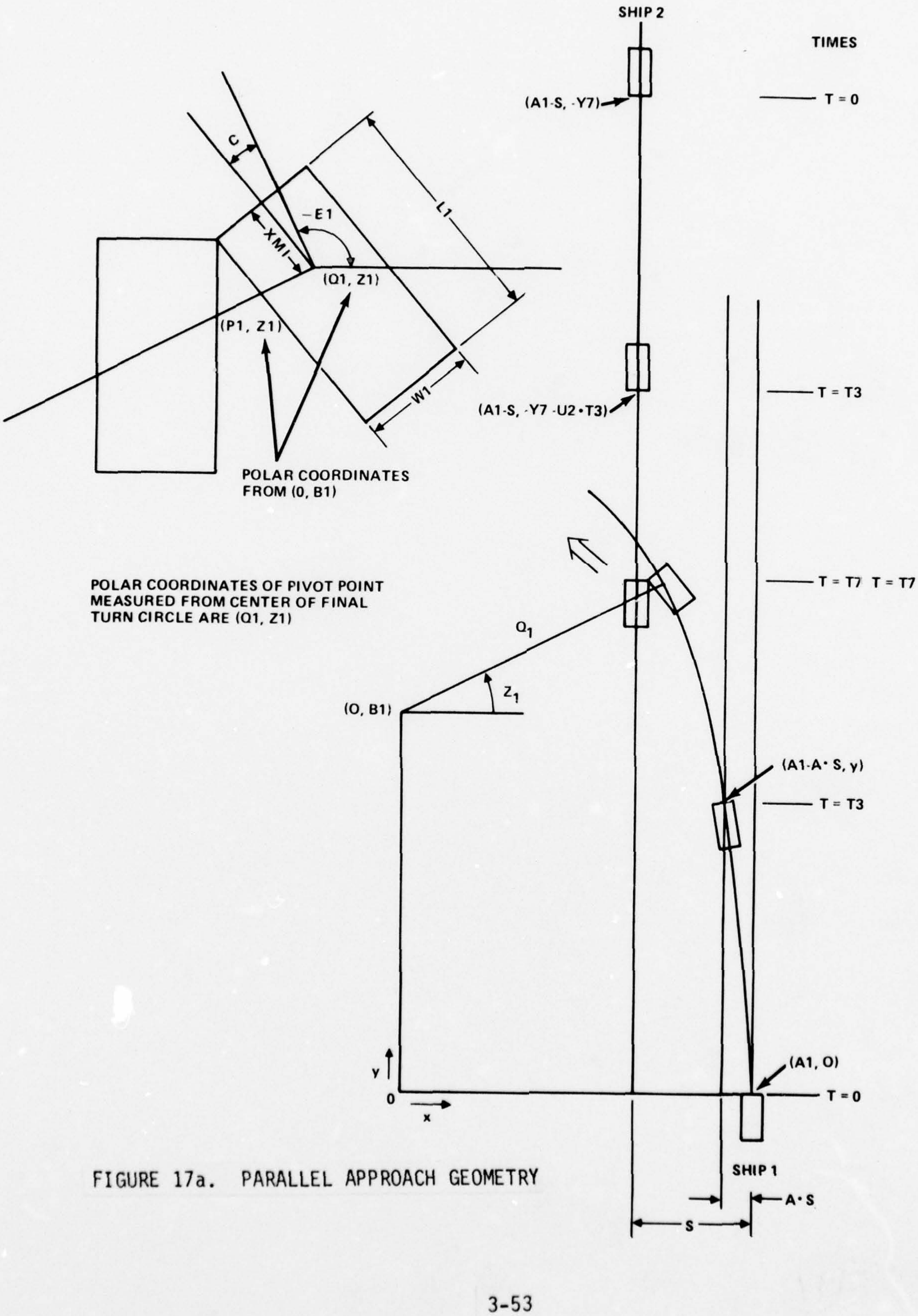


FIGURE 17a. PARALLEL APPROACH GEOMETRY

taken to be t = 0. At t = 0, ship 1 is traveling at an input initial speed. As the turn progresses, the changing speed of ship 1 is computed along with its changing position. That is the function of subroutine SPIRAL. In the figure the bow of ship 1 is at (A1,0) and, for the front of the collision region, the bow of ship 2 is at (A1-S,-Y7), i.e., the bow of ship 2 is S (the separation distance) to the left of and -Y7 above ship 1. The distance -Y7 is computed later. At time t = 0, ship 2 has not yet taken action. At time T3 the erring vessel has reduced the separation distance to the α1 response of ship 2 and now ship 2 begins his evasion. So at time T3 the x-coordinate of the bow of ship 1 is at A1-A·S (A = α1) and the bow of ship 2 is at (A1-S, -Y7-U2·T3).

We now shift our attention to the points (one on either side) which are to collide. For the front of the collision region these points are the port-bow of ship 1 and the port-stern of ship 2. At time T7 these two points coincide, as indicated in the following time sequence.

TIME SEQUENCE

Time	Ship 1	Ship 2
0	Bow at (A1,0), beginning spiral turn across path of ship 2.	Bow at (A1-S, -Y7), continuing course and speed.
T3	Bow at (A1-A·S, y), continuing on spiral turn.	Bow at (A1-S, -Y7-U2·T3). Now alert, begins evasive action.
T7	Port-bow at: X = P1 · COS(Z1) - XM1 · COS(E1-C1) Y = B1 + P1 · SIN(Z1) + XM1 · SIN(E1-C1). P1 = Q1 - $\frac{1}{2}$W1 XM1 = F1 · XL1 F1 = 1/3 P1 = radial distance to port side from center XM1 = distance from pivot point to bow.	Port-stern at same point.

Two other points of the collision region are next found, i.e., the middle point and the rear point. The middle of the collision region is characterized by a bow-to-bow collision and the rear of the collision region is characterized by the starboard-stern of ship 1 colliding with the starboard-bow of ship 2.

One point to bear in mind in all of the collision region considerations is that whereas the erring ship has a unique position as a function of time, the unerring ship does not. In fact, the collision region is made up of the totality of many possible starting positions of ship 2.

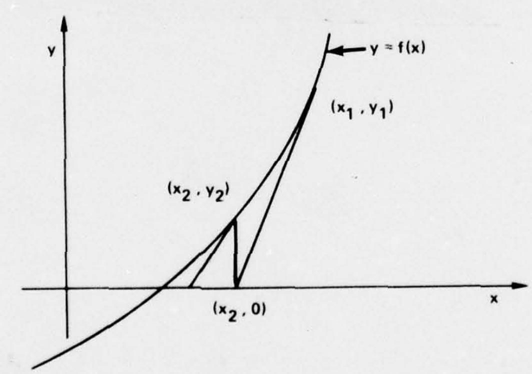
The method of computation deserves a note. For the colliding vessels, first the time is found by making the two x-coordinates equal. Then the y-coordinates are set equal. Given the collision point, the elapsed time, and the response taken by ship 2, the initial point (Al-S, -Y7) of ship 2 is computed.

Having found the collision region, a series of collisions is considered (2N points), to provide a range of inputs to the energy transfer model. Figure 17b illustrates the six collisions for N=3. The location of each collision is found by solving for equal coordinates for specific points on ships 1 and 2. The solution is an approximation (within one foot) using Newton's iterative method.

Newtonian Method for Solving an Equation of the Form $f(x) = 0$

The geometric motivation behind the method is:

1. Find a point (x_1, y_1) on the curve $y = f(x)$.
2. Approximate $f(x)$ by the line tangent to $y = f(x)$ at (x_1, y_1).
3. Find where this line crosses the x-axis. Call this point $(x_2, 0)$.
4. Find the point on the curve (x_2, y_2).
5. *Repeat.*



NEWTONIAN ALGORITHM

Suppose we have found (x_n, y_n) with $y_n = f(x_n)$. The line tangent to $y = f(x)$ at the point (x_n, y_n) is given by:

$$y = f(x_n) + (x - x_n)f'(x_n)$$

where $f'(x) = df/dx$. This line crosses the x-axis at $x_{n+1} = x_n - f(x_n)/f'(x_n)$. This is the recursion equation for Newton's method.

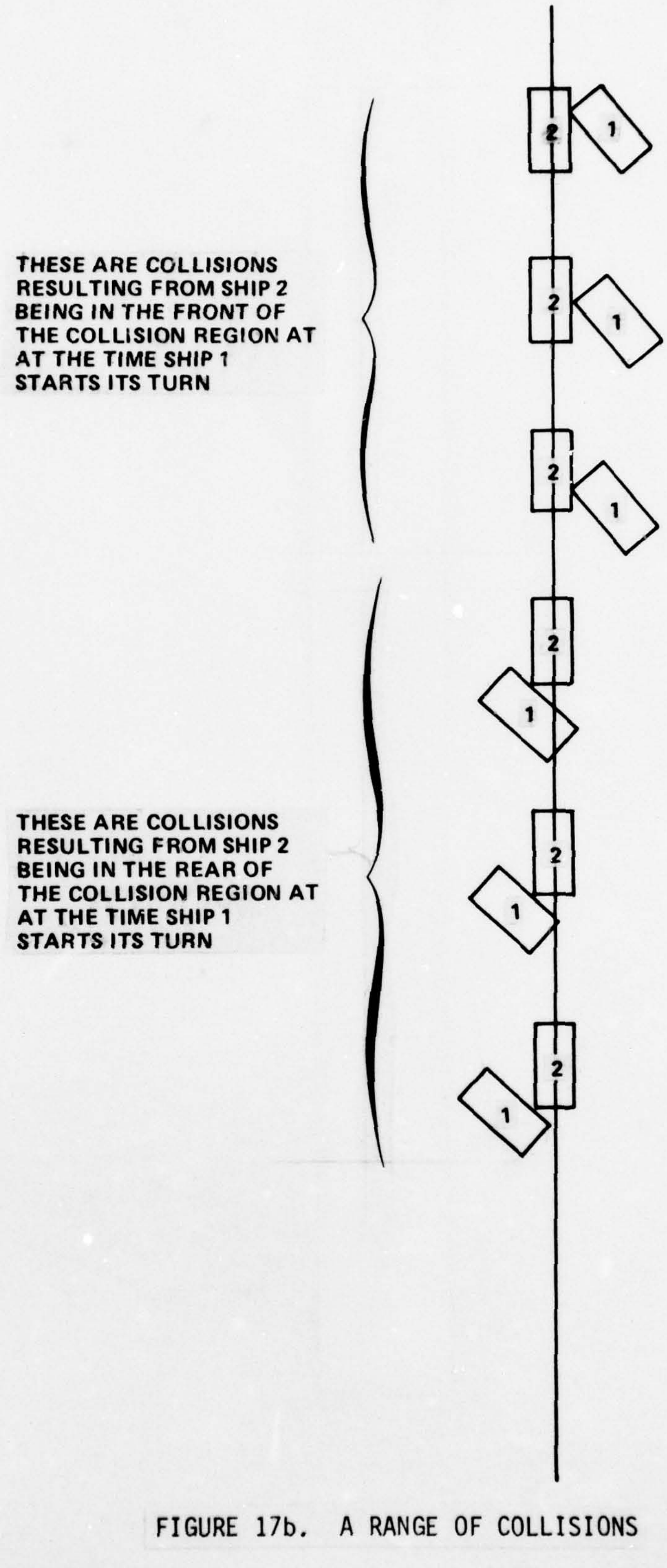


FIGURE 17b. A RANGE OF COLLISIONS

RELATIONSHIPS AMONG THE SYSTEMS PARAMETERS

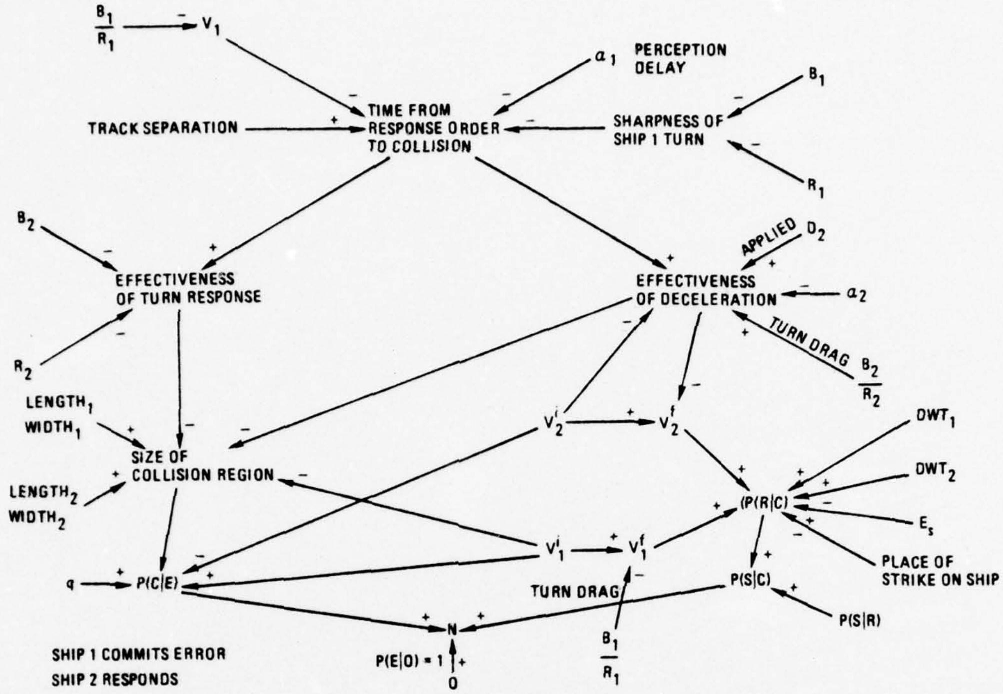
At the beginning of this section, a brief mention was made about the relations between the system parameters and the spill equation. The previous discussion describes much about what the model inputs are and how they are used. Figure 18 further aids understanding how these parameters integrate into the system and how the conditional probabilities are determined. It should be noted that the diagram is not all inclusive of all possible scenarios, but this one diagram is sufficiently representative.

Sensitivity of a limited sort may be quickly conducted with the diagram. By "limited sensitivity" we mean that the direction of cause-effects are revealed although not the degree of the effect. The utility of the diagram arises not only from this "direction-of-effect" evaluation, but also from enabling one to understand the way in which all the parameters are linked together. Thus, a more intuitive "feel" for the system may be possible.

To read the diagram, one first picks a parameter and asks the question, "If I increase the value of this parameter, what will be affected and will the effect be positive or negative in direction?" One may start with any parameter and follow the cause-effect chain to the end point, N—the expected number of spills. At each link in the sequence the question is repeated. After a "-" is encountered in any particular sequence, then a subsequent "+" would mean the effect would be in the same direction. Or, to state the situation somewhat differently, an arrow with a "+" at the head indicates that a decrease in the value of the parameter at the tail will result in a decrease in the value of the system value being influenced. On the other hand, with a "-" a decrease in value will have an increase effect on the variable being influenced.

For illustration, suppose the spiral tail of Ship 1 is lengthened. Then the turn sharpness is decreased, and then the time from the response action initiation to collision is increased. This then increases the effectiveness of the deceleration response (assume no turn is executed for the response), which reduces both the size of the collision region and the final velocity upon collision. Since the collision region size is reduced, the $P(C|E)$ is reduced and the expected number of spills is less. At the same time, since the velocity upon impact is less, the $P(R|C)$ will be reduced as will the $P(S|R)$ and the expected number of spills.

For any parameter, a similar sequence could be traced through the diagram.



SYSTEM PARAMETERS

TURN PARAMETERS

- R_1, R_2 – STEADY–TURNING RADIUS
- B_1, B_2 – ADVANCE LESS STEADY–TURNING RADIUS

RESPONSE PARAMETERS

- α_1 – % DECREASE IN INITIAL TRACK SEPARATION AT WHICH RESPONSE IS INITIATED
- α_2 – TIME TO DEVELOP FULL REVERSE THRUST
- $\frac{B_1}{R_1}, \frac{B_2}{R_2}$ – INDICATOR OF AMOUNT OF DECEL IN TURN
- D – STEADY - DECELERATION RATE

OTHER VESSEL PARAMETERS

- V_1^i, V_2^i – INITIAL VELOCITY
- V_1^f, V_2^f – IMPACT VELOCITY
- E_S – ENERGY REQ'D FOR HULL RUPTURE

SCENARIO PARAMETERS

- q – RATE AT WHICH SHIP 1 COMMITS TURN ERROR PER UNIT DISTANCE
- N – EXPECTED NO. OF SPILLS
- O – NO. OF OPPORTUNITIES FOR EXPOSURE TO COLLISION
- E – EXPOSURE – NO. OF MEETING ENCOUNTERS
- C – COLLISION
- R – HULL RUPTURE
- S – SPILL

FIGURE 18. SYSTEM PARAMETER INFLUENCE DIAGRAM FOR PARALLEL MEETING SCENARIO IN WHICH VESSEL 1 TURNS ACROSS CHANNEL INTO PATH OF VESSEL 2

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III. SCENARIO MODEL: DEMONSTRATION

INTRODUCTION

One significant area of potential use for the maneuvering model is assistance to U.S. Coast Guard Captains of the Port (COTP) in the development of initiatives for reducing collisions in specific danger areas. Examples of the type of actions that a COTP may take are speed restrictions on hazardous polluting substance (HPS) carriers and on other ships sharing a channel with the HPS carrier, prohibitions on ships above a certain size entering a channel segment during an HPS carrier passage, and prohibitions against ships overtaking and passing HPS carriers in certain areas. The potential gains from all of these could be tested in the analytic model.

To demonstrate the manner in which the analytic model might be applied, we have selected several systems which include all essential features of a real world situation. The many details which would be used in an actual application related to a specific waterway and its shipping have been excluded. The primary purpose of this demonstration is to show how changes in various system parameters might influence the expected number of HPS spills. For the demonstration we will use the simplest form of the generalized waterway model described in Appendix E of our previous report. [1] For the parallel meeting and overtaking scenarios, the model concerns one channel segment, one ship type and a single pair of ships. The measure of effectiveness used for each parameter change is discussed in the following subsection. Further on, baseline cases are defined and the results of the sensitivity analyses are presented in graphic format.

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[1] Dunn, William A., et al., Spill Risk Analysis Program, Phase II, Methodology Development and Demonstration, U.S. Coast Guard Report No. CG-D-15-75 (AD 785026), August 1974.

MEASURE OF EFFECTIVENESS

As stated in Section II, the basic measure of effectiveness is the relative change caused by a selected system change in the expected number of spills, during some time period, in some body of water. Since our demonstration uses a single channel segment the baseline case number of spills can be written as Equation (3.1)

$$N_o = O_o P(E_o | O_o)\ q D_o (E_{d_o} \geq E_{s_o}) P_o(HPS) \tag{3.1}$$

where

O_o = The number of opportunities for exposure

$P(E_o | O_o)$ = The probability of exposure in the parallel approach scenario given an opportunity

q_o = The rate of occurrence of potential collision causing errors per unit distance traveled

D_o = The distance the erring vessel travels during which the turn error would produce a collision

E_{d_o} = The energy available for deforming plate

E_{s_o} = The strain energy which can be absorbed by the struck ship prior to rupture

$P_o(HPS)$ = The probability that a hazardous or polluting substance will be spilled if the struck ship ruptures

$P(E_{d_o} \geq E_{s_o})$ = The probability that E_{d_o} exceeds or equals E_{s_o} for a given collision.

If N' is the number of spills expected to occur in a given channel following the implementation of a Coast Guard action, then the relative change in the expected number of spills as given in Equation (3.2) is taken as the effectiveness of the action.

$$\frac{\Delta N}{N_o} = \frac{N' - N_o}{N_o} = \left(\frac{N'}{N_o}\right) - 1 = \frac{O' P(E' | O') q' D' P(E'_d \geq E'_s) P'(HPS)}{O_o P(E_o | O_o) q_o D_o P(E_{d_o} \geq E_{s_o}) P_o(HPS)} - 1. \tag{3.2}$$

For purposes of this demonstration we assume that the Coast Guard actions considered will not change O_o (the traffic), q_o (the error rate), or $P_o(HPS)$ (the cargo mix), that is $O_o = O'$, $q_o = q'$, and $P'(HPS) = P_o(HPS)$. Therefore the relative change, $\Delta N/N_o$, can be written as shown in Equation (3.3).

$$\frac{\Delta N}{N_o} = \frac{P(E'|O')D'P(E'_d \geq E'_s)}{P(E_o|O_o)D_oP(E_{d_o} \geq E_{s_o})} - 1. \tag{3.3}$$

If an action causes changes in either O_o, q_o, or $P_o(HPS)$, without affecting the other parameters, then $\Delta N/N_o$ is given by the appropriate form of Equation (3.4)

$$\begin{aligned} \Delta N/N_o &= (O'/O_o) - 1 \\ &= (q'/q_o) - 1 \\ &= (P'(HPS)/P_o(HPS)) - 1. \end{aligned} \tag{3.4}$$

BASELINE CASE PARAMETER VALUES

In the Phase II final report of this study, 2/ a "baseline case" was developed to perform sensitivity analysis using the various parameters. In this report the same values are also used, with the addition of a new response parameter $Alpha_2$—a time lag delay from perception of threat to full action by the ship. This response-time lag is applied in the case where deceleration or acceleration is applied. Any time lag inherent in turning is subsumed in the long tail of the spiral turn. Ship width (beam) and the spiral turn parameters described in the last section are also added.

Meeting and Overtaking Scenarios

The baseline case values refer to the dimensions of the tanker Esso Suez having approximately the following characteristics:

Vessel

1.	Length	600 feet
2.	Beam	85 feet
3.	Gross weight	35,000 long tons displacement

2/ Ibid.

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4. Crabbing angle — 5 degrees into turn

5. Pivot point — 1/3 from bow

6. Strain energy for hull rupture — 10^8 ft/lbs

Response

1. Maximum deceleration — .05 ft/sec

2. Time lag-deceleration — 60 seconds

3. Spiral turn:

   — Advance minus radius — 1,250 ft

   — Steady-state turn radius — 1,000 ft

   — Transfer to steady-state radius ratio — 1.15:1.0

Scenario

In addition to these ship parameters, there are others which relate specifically to the parallel meeting and overtaking scenarios. $Alpha_1$ is 20 percent of the channel separation. In this report, the same $Alpha_1$ is used as in the previous report, however, the additional time lag, $Alpha_2$, is added to the total response to incorporate time delays in deceleration. We are assuming that Vessel 2 (the "defending" ship) is trying to avoid collision. Vessel 1 (the "erring" ship) makes a normal turn following its spiral path. Vessel 2 does not accelerate, decelerate or change course or speed after initiation of its turn. In other words, there is no possibility of corrective maneuvers by Vessel 1 at some point after reducing the separation between the paths of the two ships by $Alpha_1$.

Other baseline values are track separation of 400 feet, vessel speeds of eight knots (overtaking vessel speed is 12 knots) and a response of maximum deceleration with no turn.

Sensitivity Tests

Sensitivity tests of the following parameters were made by varying these parameters over the range shown.

Parameter	Range
Track separation	200-1,000 ft
$Alpha_1$	0.1-0.7 · track separation (S)
$Alpha_2$	20-120 seconds
Deceleration	0-.14 ft/sec^2
Turning characteristics (B and R together)	
Advance minus steady-state turn radius (B)	250-2,000 ft
Steady-state turn radius (R)	600-1,300 ft
Velocity	
Ship 1	4-16 knots
Ship 2	4-16 knots
Both Ship 1 and Ship 2	4-16 knots.

Long-Range Crossing Scenario

For the long-range crossing scenario different baseline case values are used. The vessels are similar to the Esso Malaysia 191,000 DWT tanker. For this vessel turning and deceleration are not as quick as for the Esso Suez type tanker in the preceding sensitivity analysis of the channel scenarios. The baseline case parameter values for this analysis are:

Vessel

1.	Length	1,000 ft
2.	Beam	156 ft
3.	Crabbing angle	5 degrees
4.	Pivot point	1/3 from bow

Response

1.	Maximum deceleration	.02 ft/sec^2
2.	Maximum deceleration with rudder cycling	.043 ft/sec^2

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3. Time lag-deceleration (α_2) 90 seconds

4. Spiral turn

— Advance minus steady-state turn radius 2,000 ft

— Steady-state turn radius 1,300 ft

— Transfer to steady-state radius ratio 1.15:1.0

Scenario

In addition to the above vessel parameters, the only other needed parameter value is the initial velocity which is 16 knots for each vessel—an approximate average cruising speed for a large tanker. 3/

Sensitivity Test

Baseline parameter values were tested for crossing angles in the range from 020 degrees relative to 110 degrees relative. In the long range crossing scenario, the give-way vessel is the "erring" vessel. The stand-on vessel is always the "defending" vessel (Ship 2) since if the give-way vessel maneuvers properly, no collision can result. The gamma (γ) angle shown in Figure 19 is measured counter clockwise from the stern of the give-way vessel.

SENSITIVITY FINDINGS

Meeting and Overtaking Scenarios

The results of the sensitivity analysis conducted using the maneuvering model for the parallel meeting and parallel overtaking scenarios are presented in Figures 19 through 34. Each figure contains the results of changing one of the system parameters over the range shown in the last subsection for three different responses (see Table 1)—no turn, left turn, and right turn, each with appropriate use of deceleration. Table 4 illustrates a sample of the sensitivity findings with indicated changes in the various system parameters as each parameter is changed by the amount shown. Table 5 shows

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3/ Sun Oil Company, Analysis of World Tank Ship Fleet - December 31, 1973, Planning and Industry Affairs Branch of Sun Oil Company, St. Davids, Pennsylvania, December 1974, p. 1.

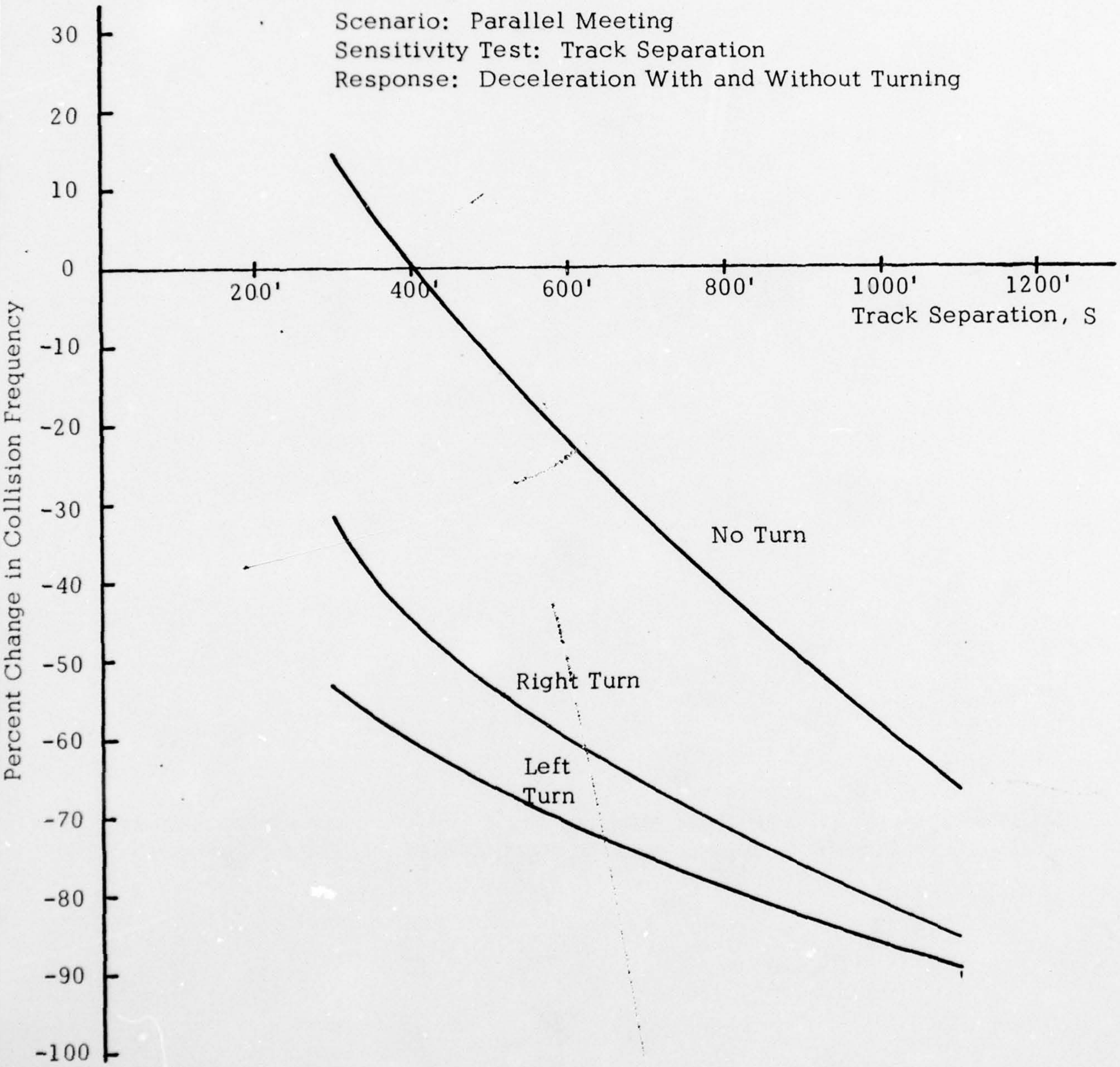

FIGURE 19. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

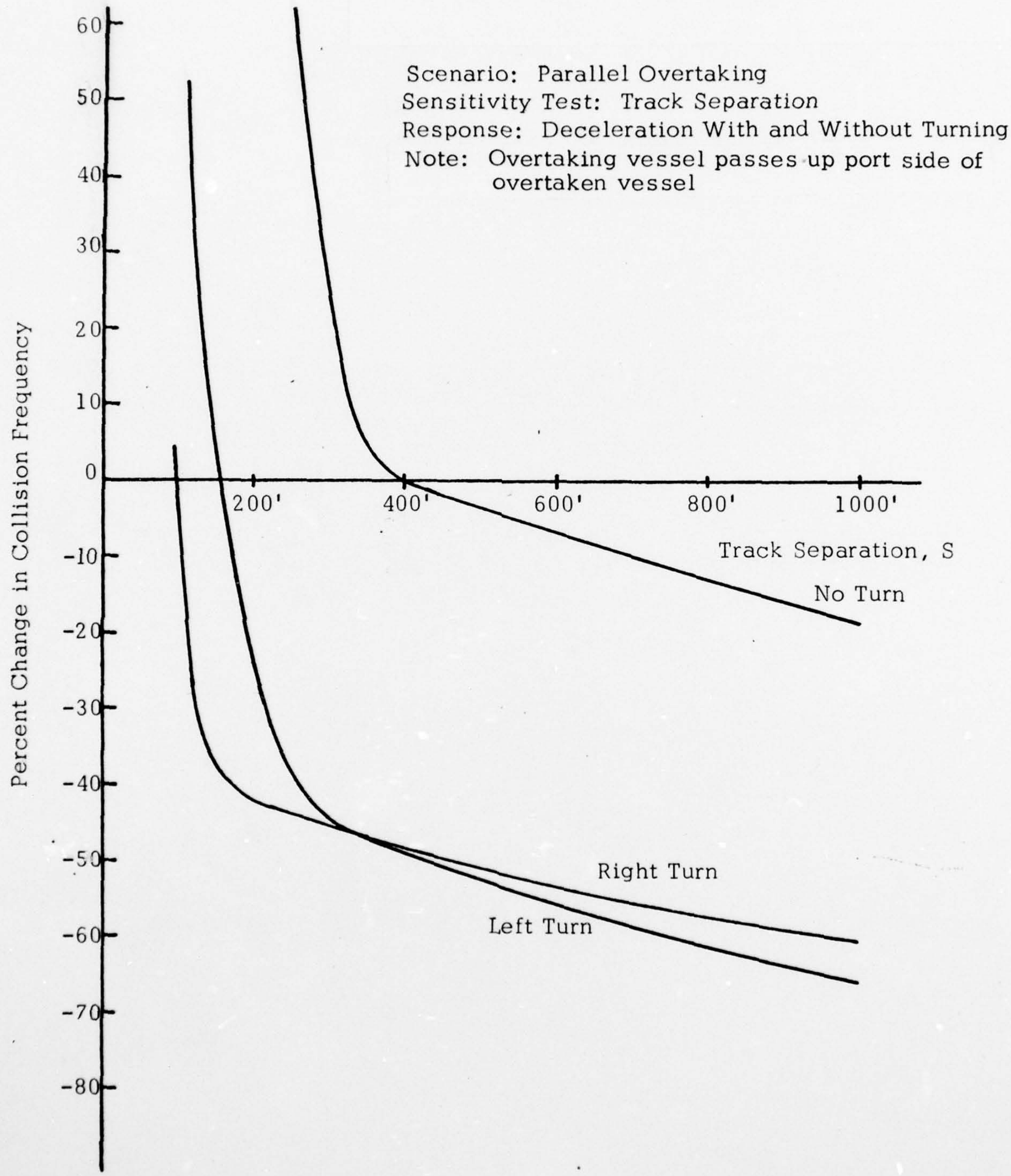

FIGURE 20. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

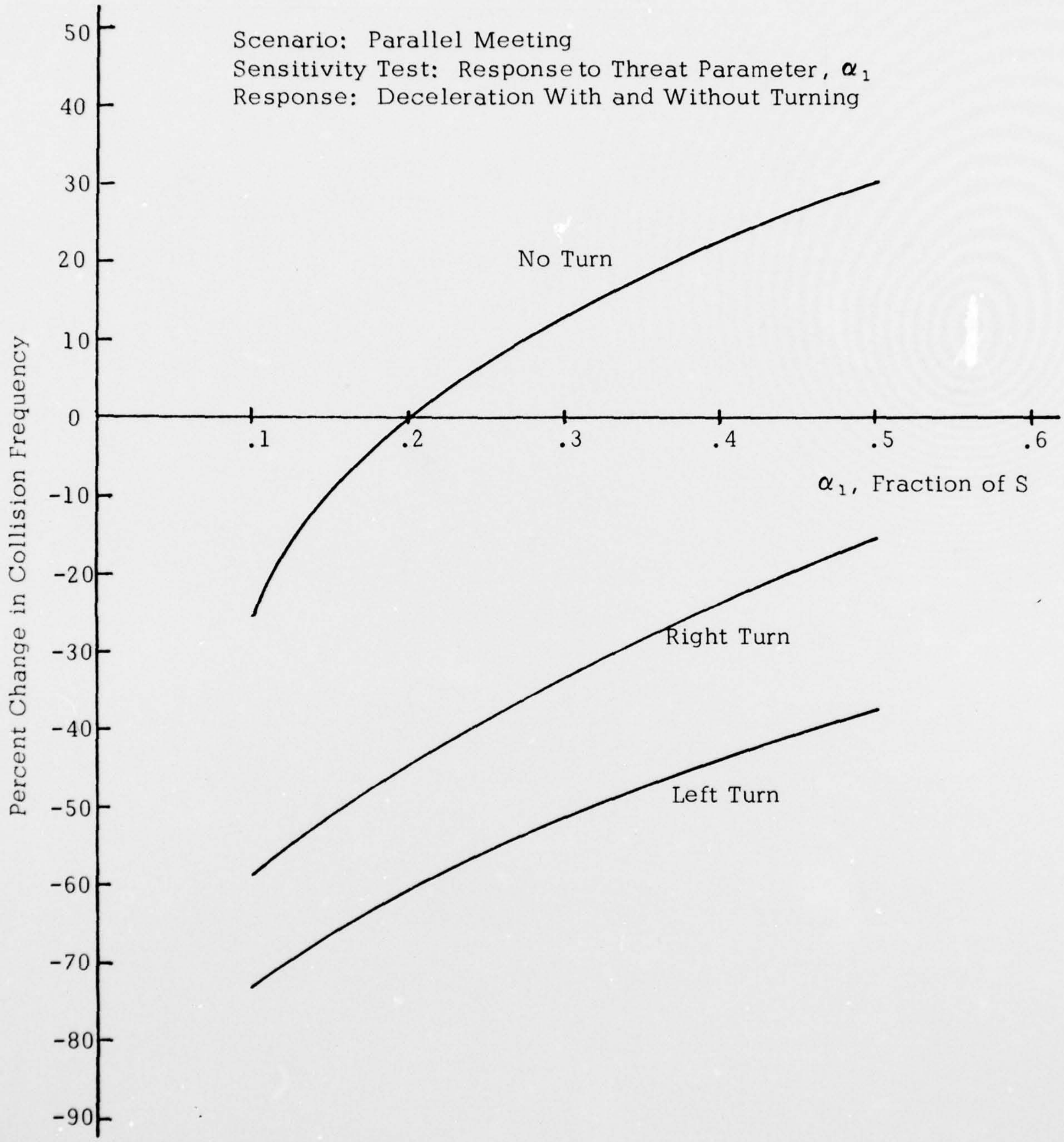

FIGURE 21. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

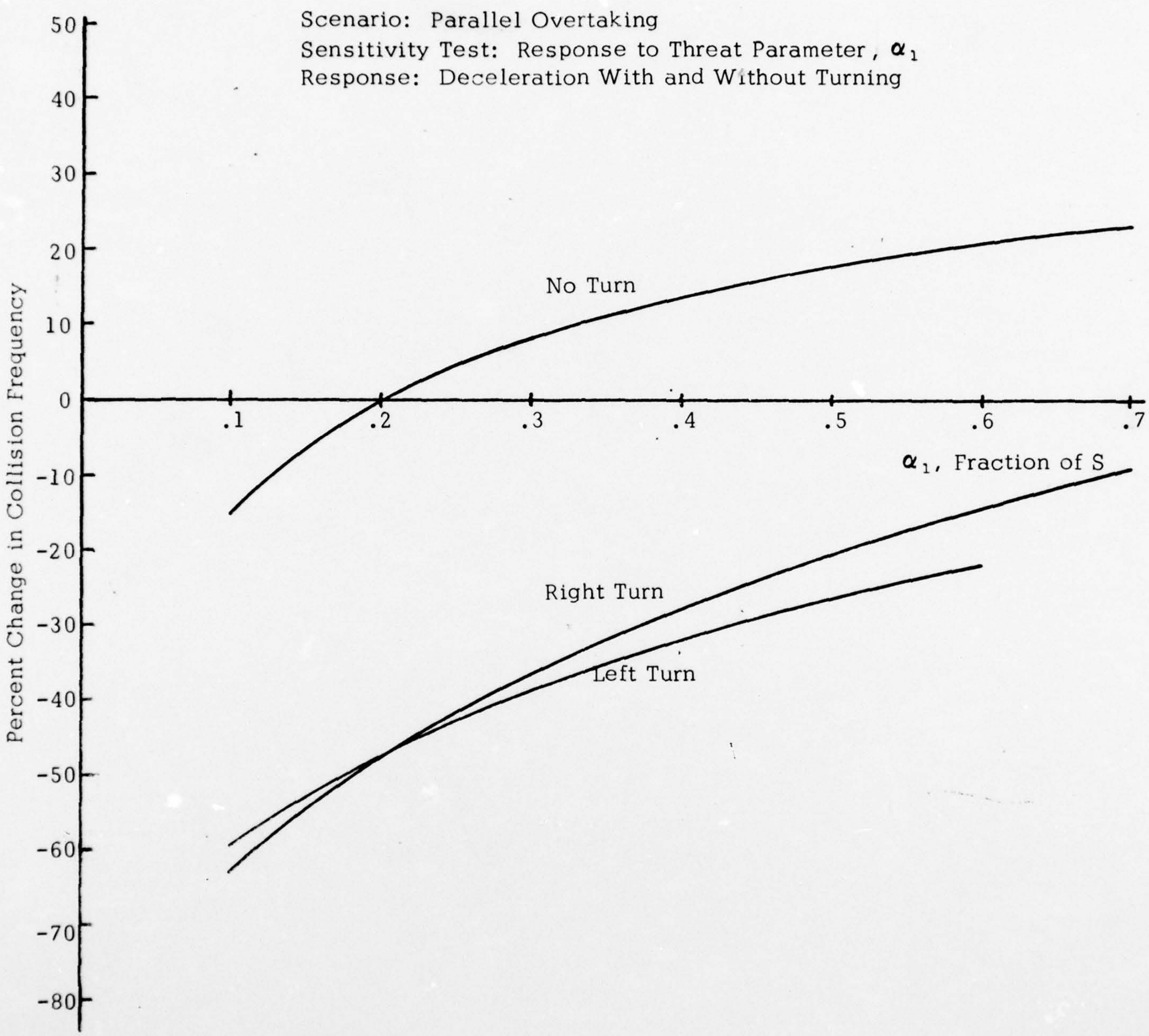

FIGURE 22. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

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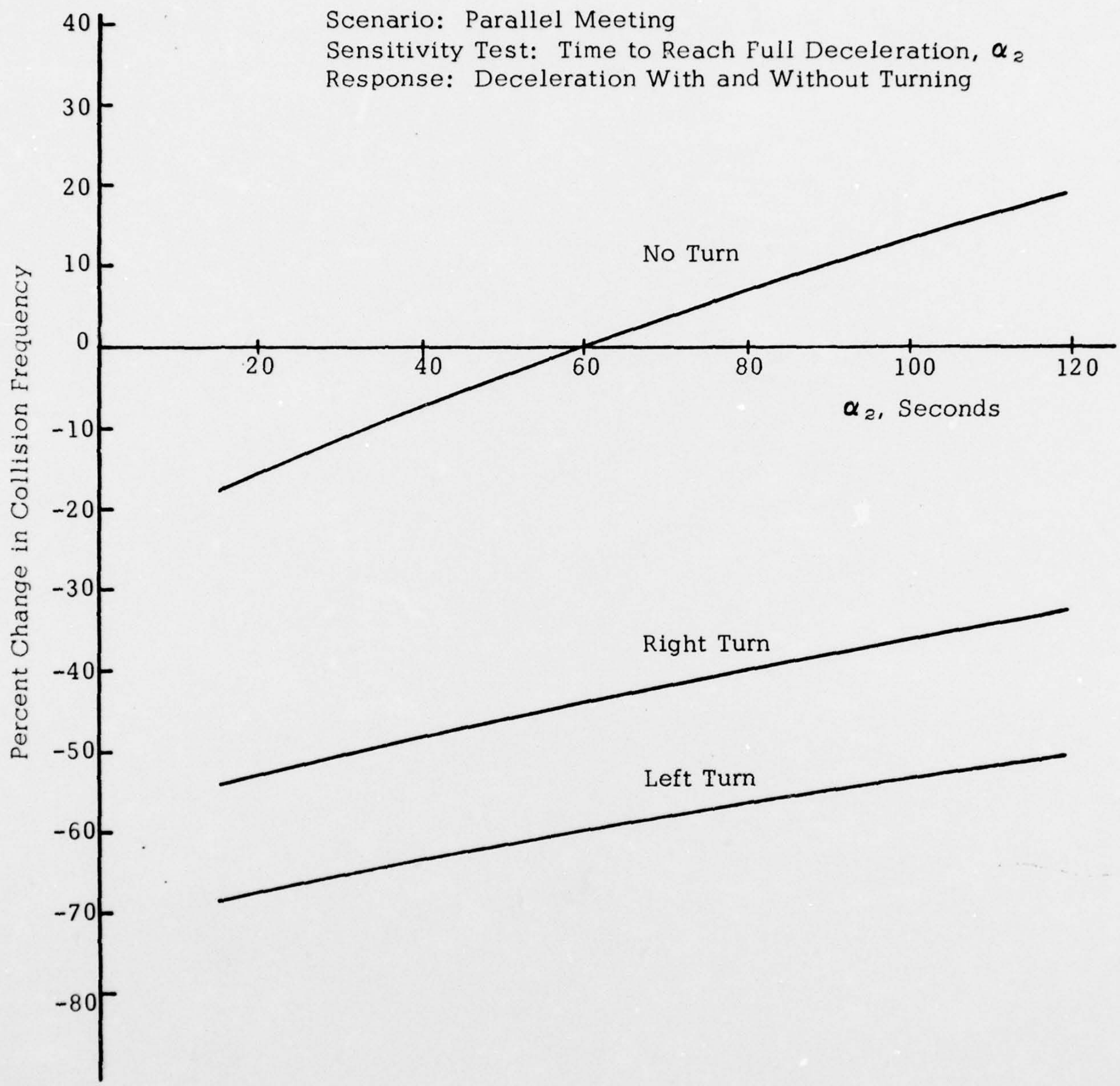

FIGURE 23. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

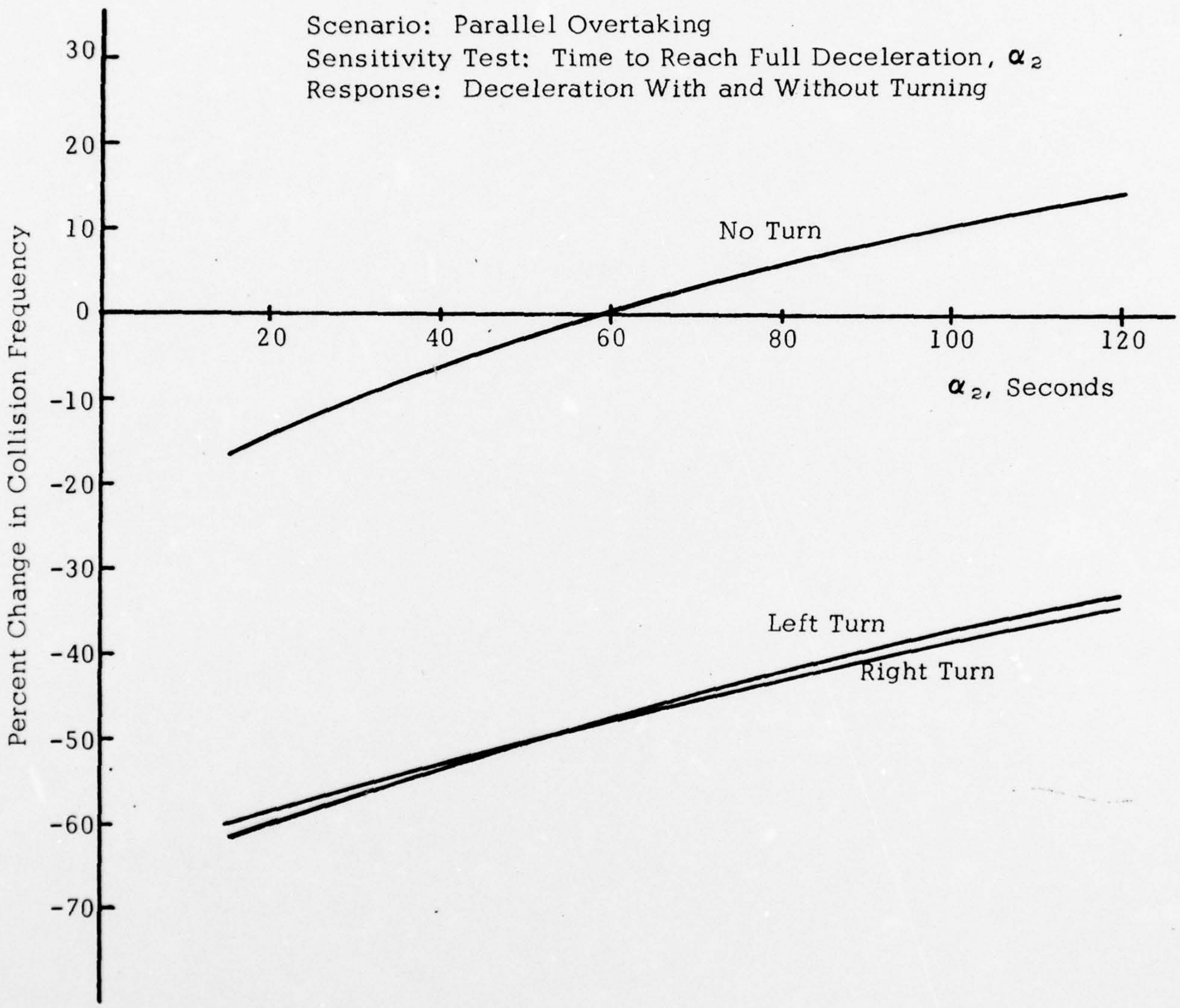

FIGURE 24. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

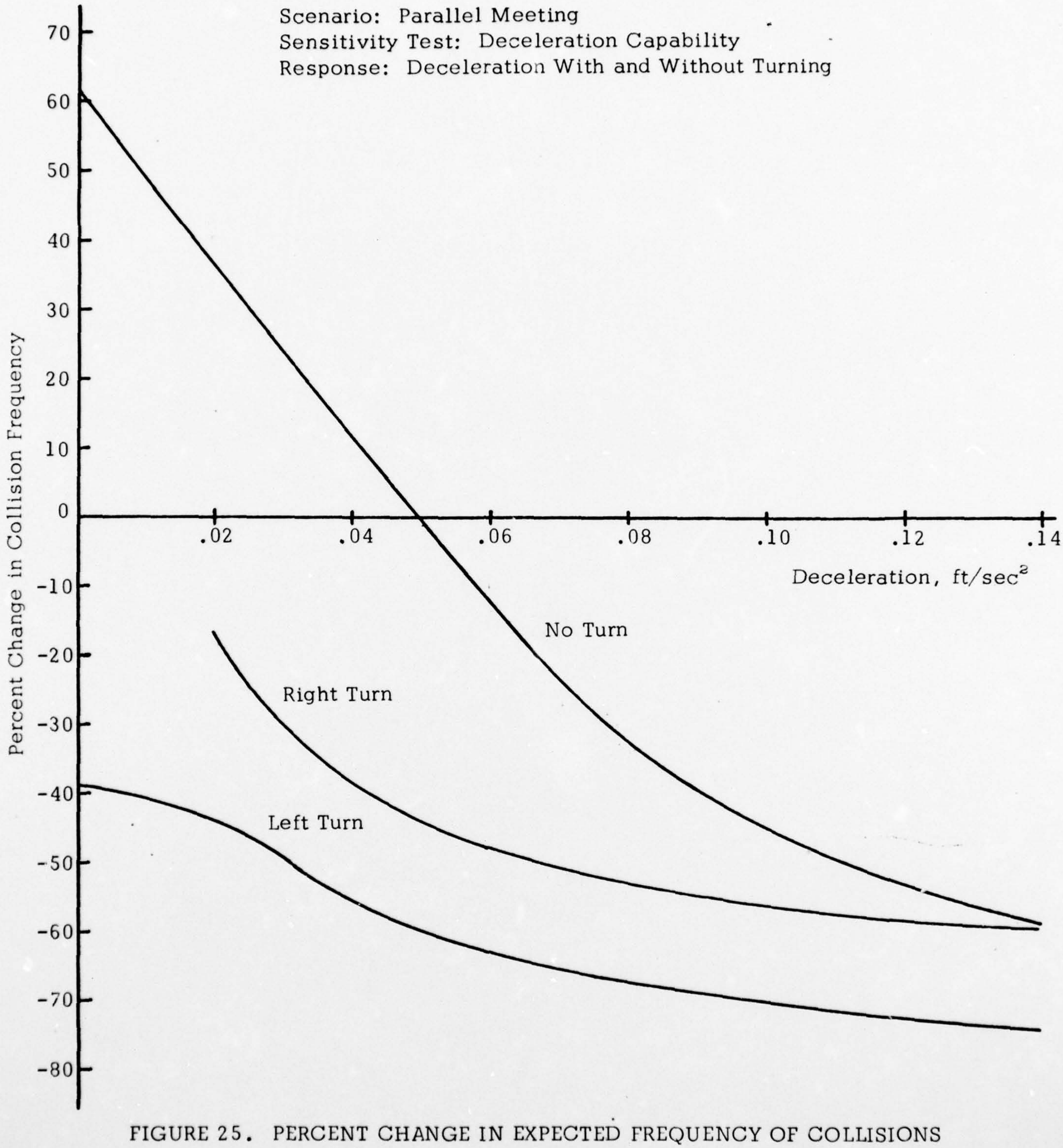

FIGURE 25. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

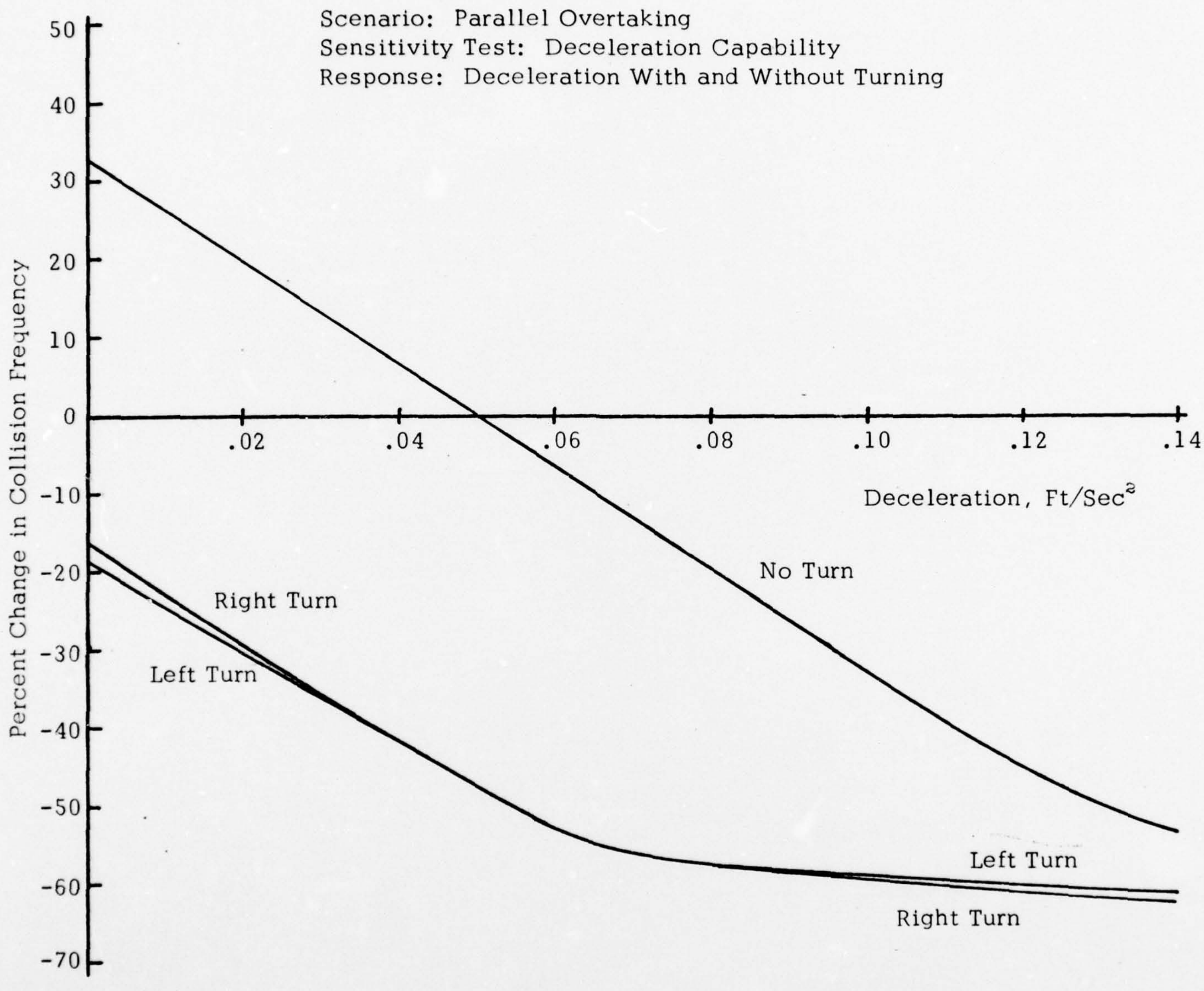

FIGURE 26. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

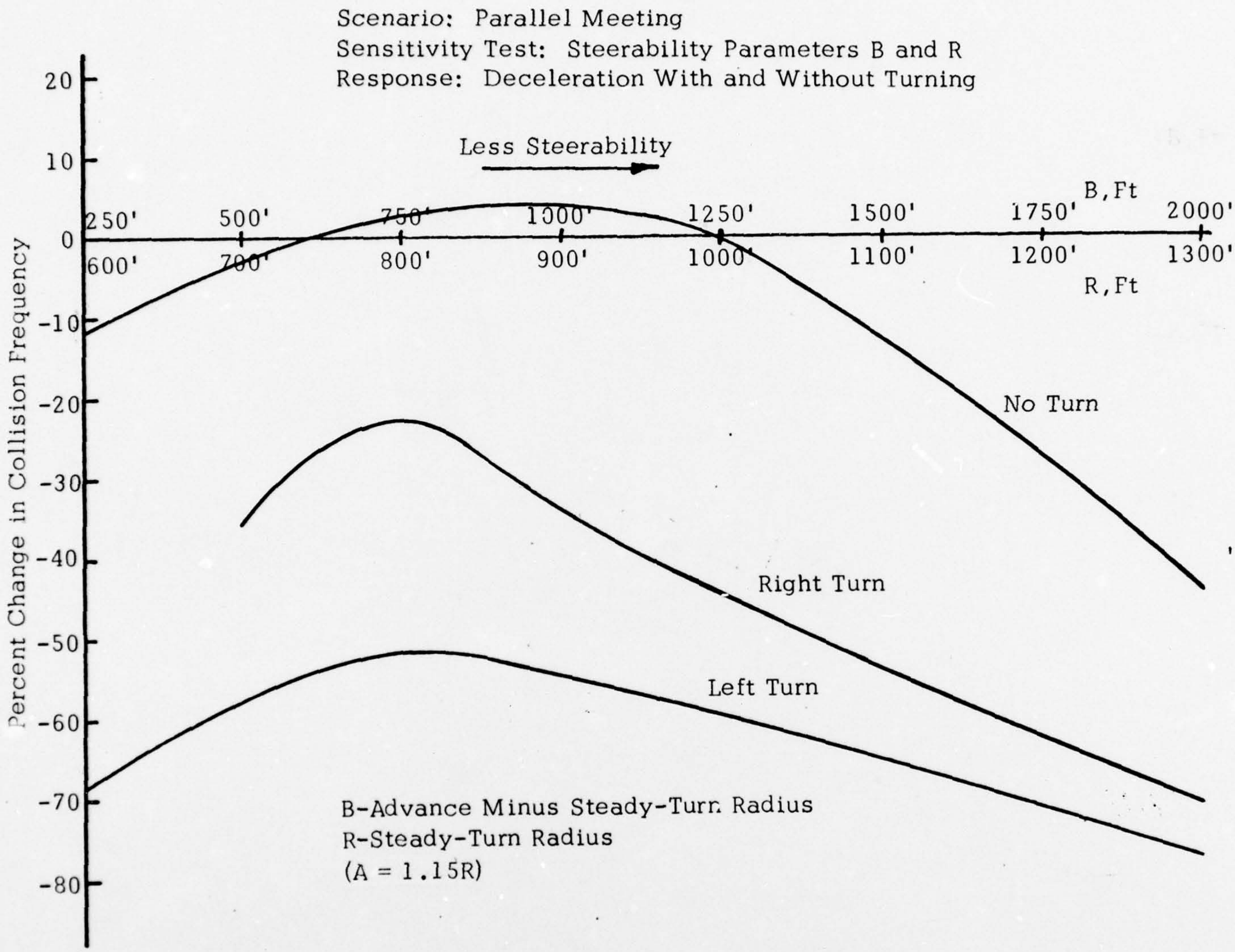

FIGURE 27. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

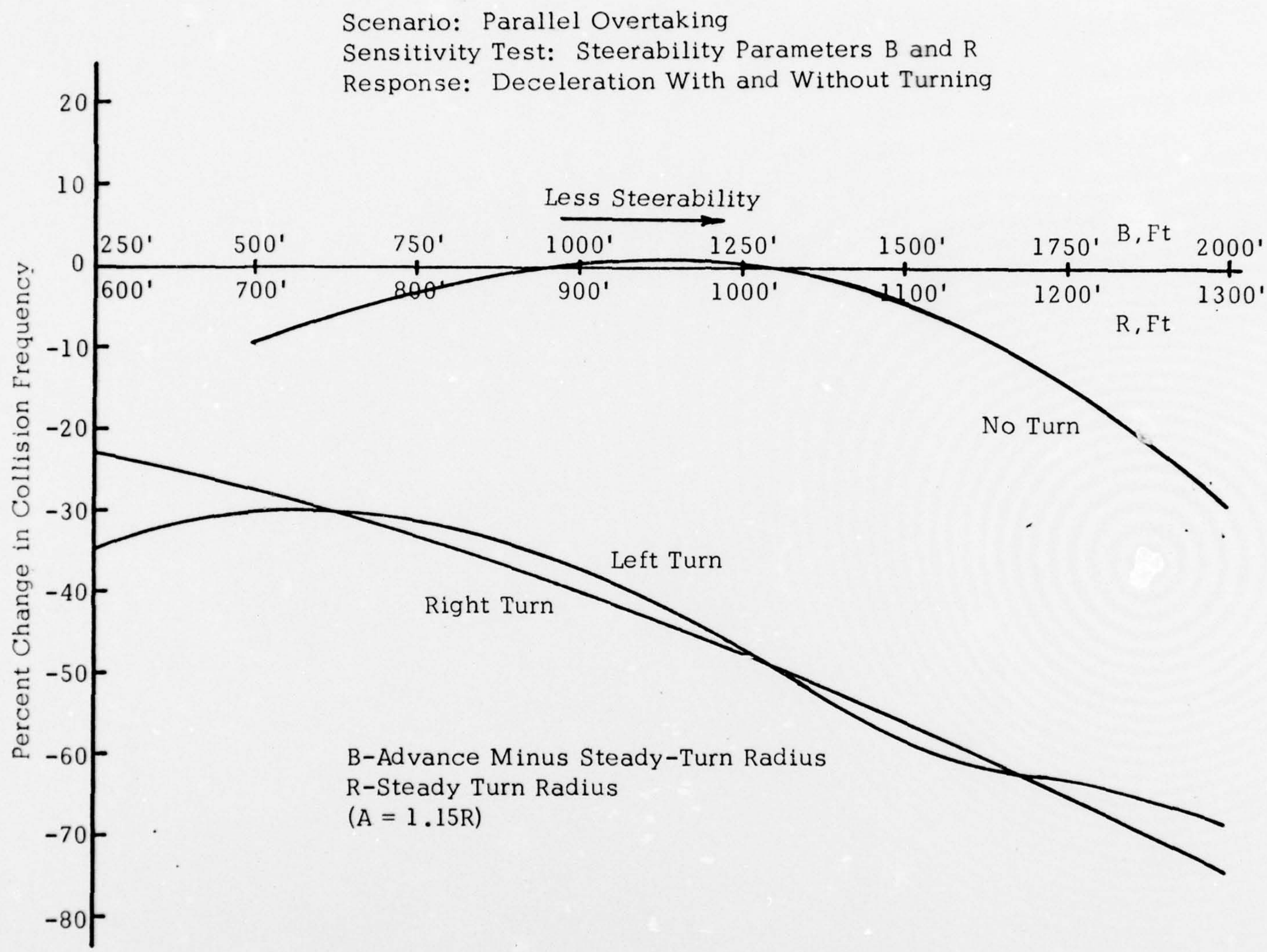

FIGURE 28. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

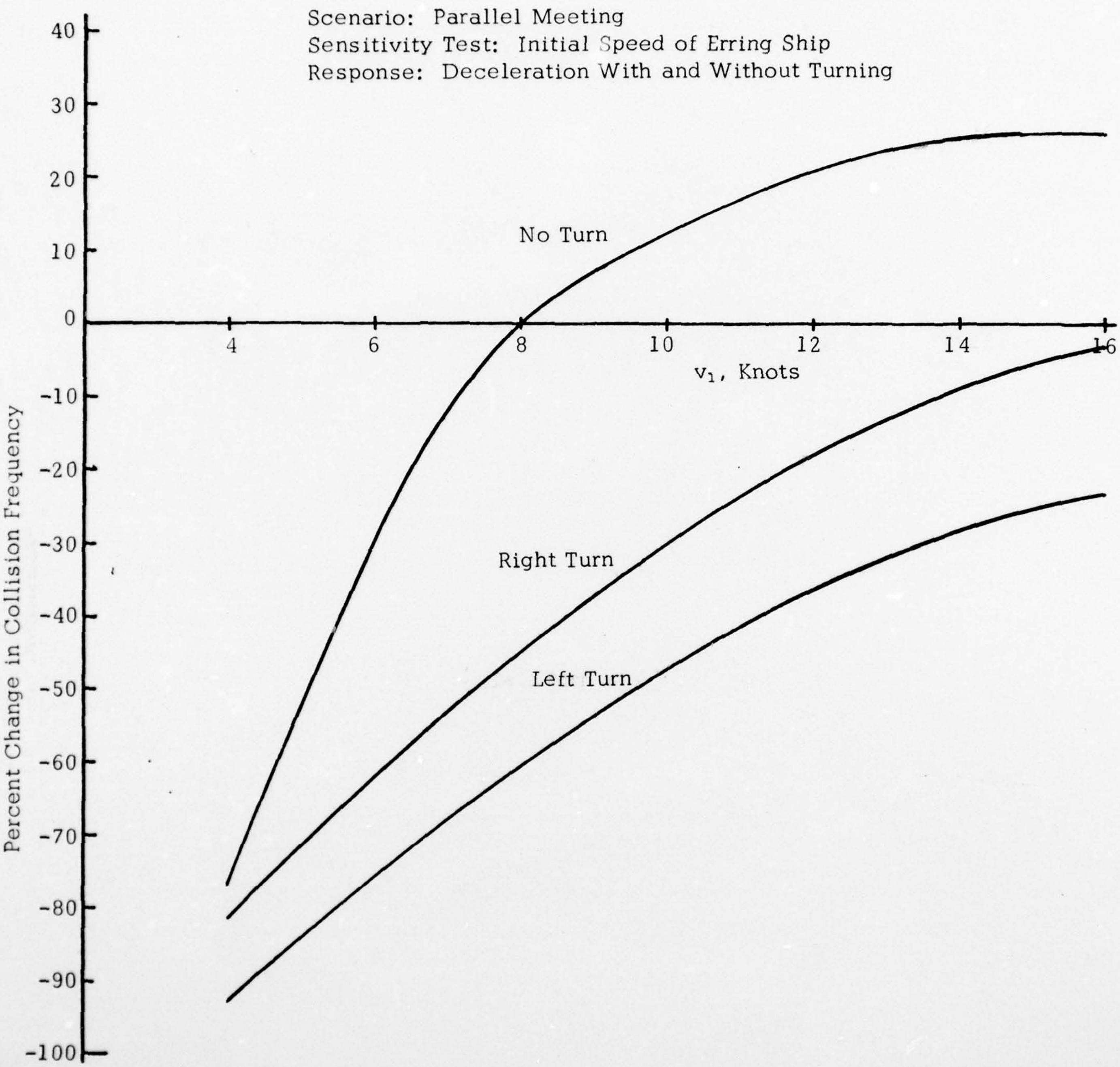

FIGURE 29. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

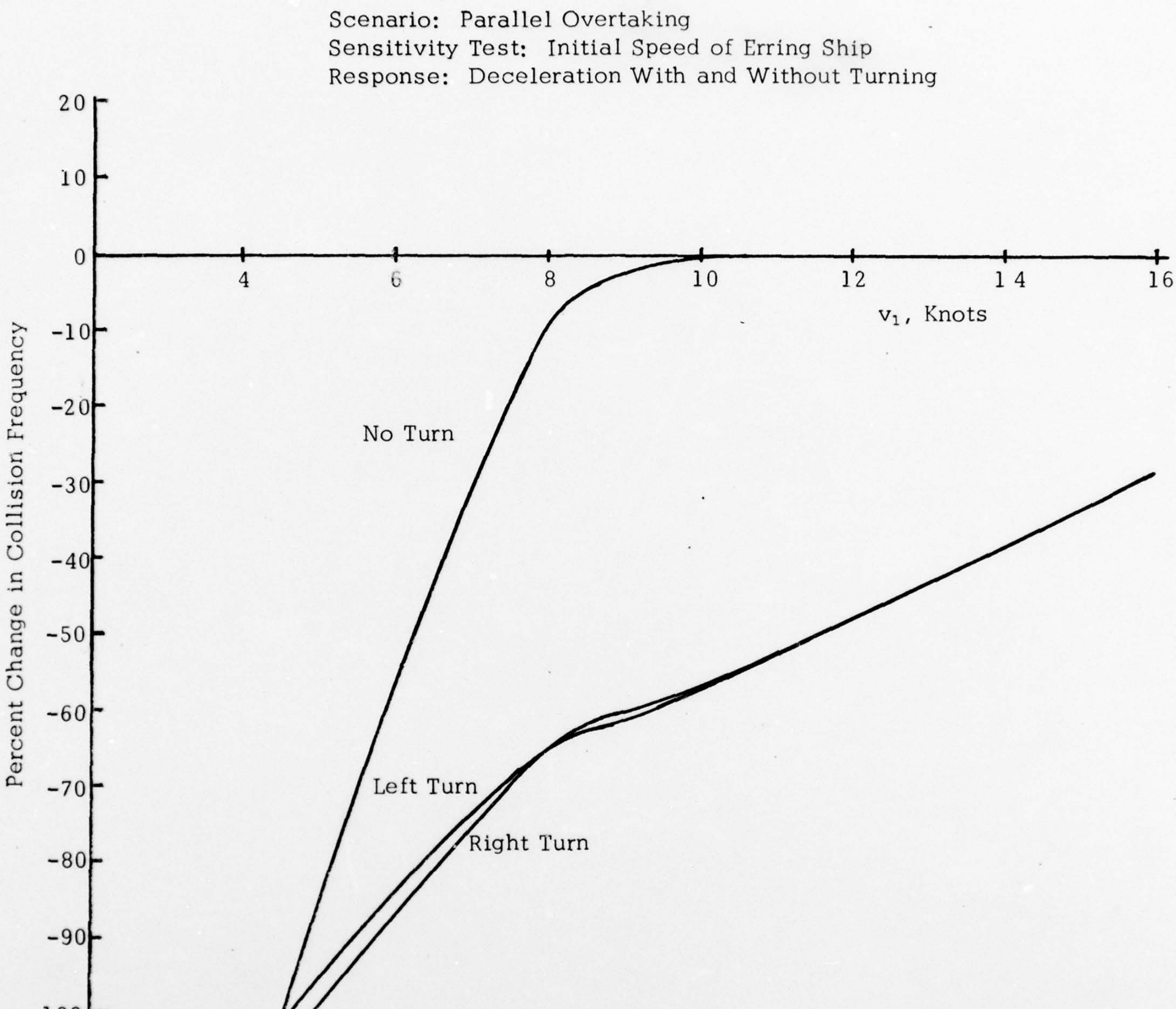

FIGURE 30. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

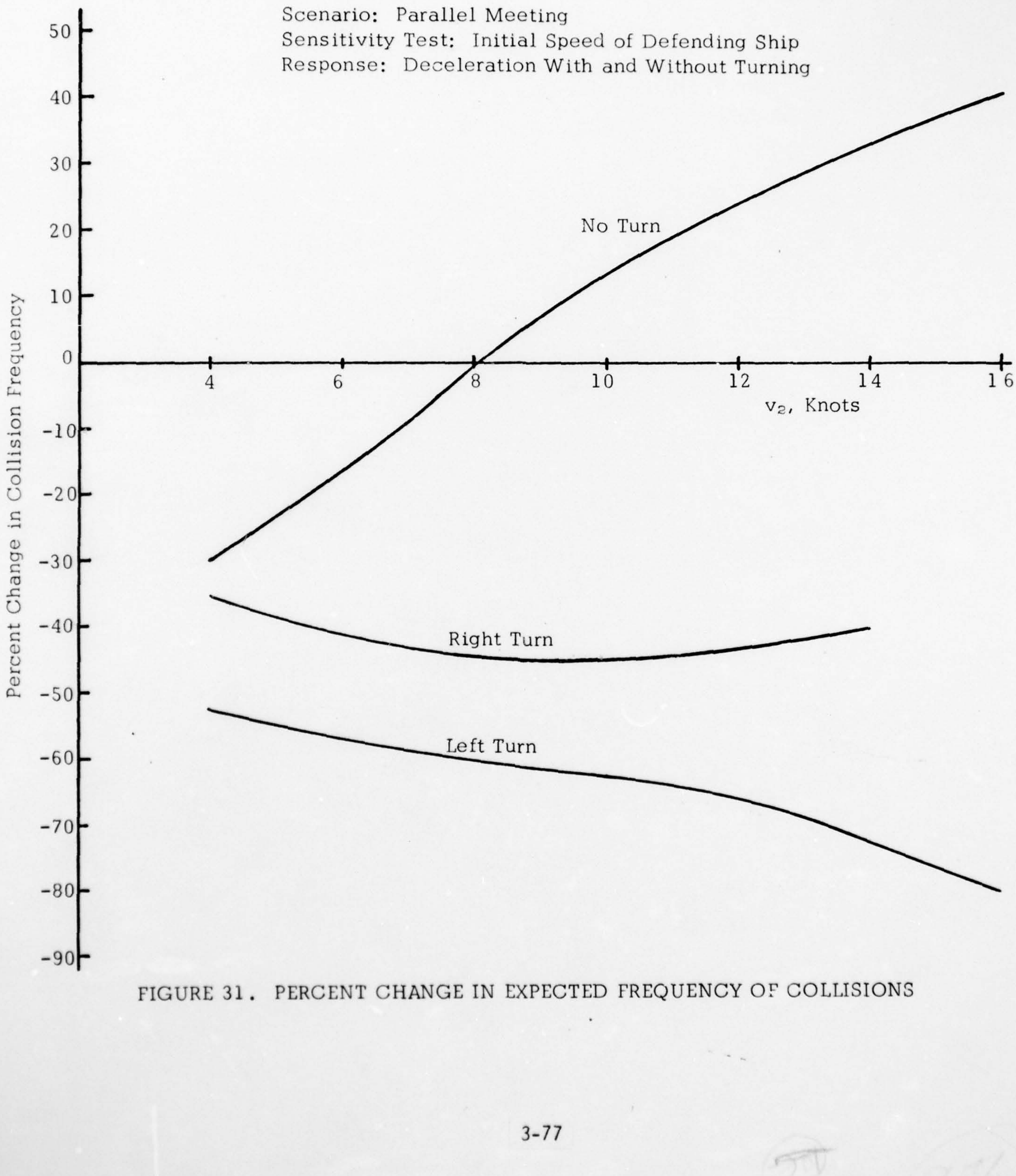

FIGURE 31. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

AD-A043 054 OPERATIONS RESEARCH INC SILVER SPRING MD RESOURCE AN--ETC F/G 13/2
SPILL RISK ANALYSIS PROGRAM. METHODOLOGY DEVELOPMENT AND DEMONS--ETC(U)
APR 77 L L STOEHR, C H MORGAN, F J REIFFLER DOT-CG-31571-A
UNCLASSIFIED ORI-TR-964-VOL-1 USCG-D-21-77 NL

3 OF 4
AD A043 054

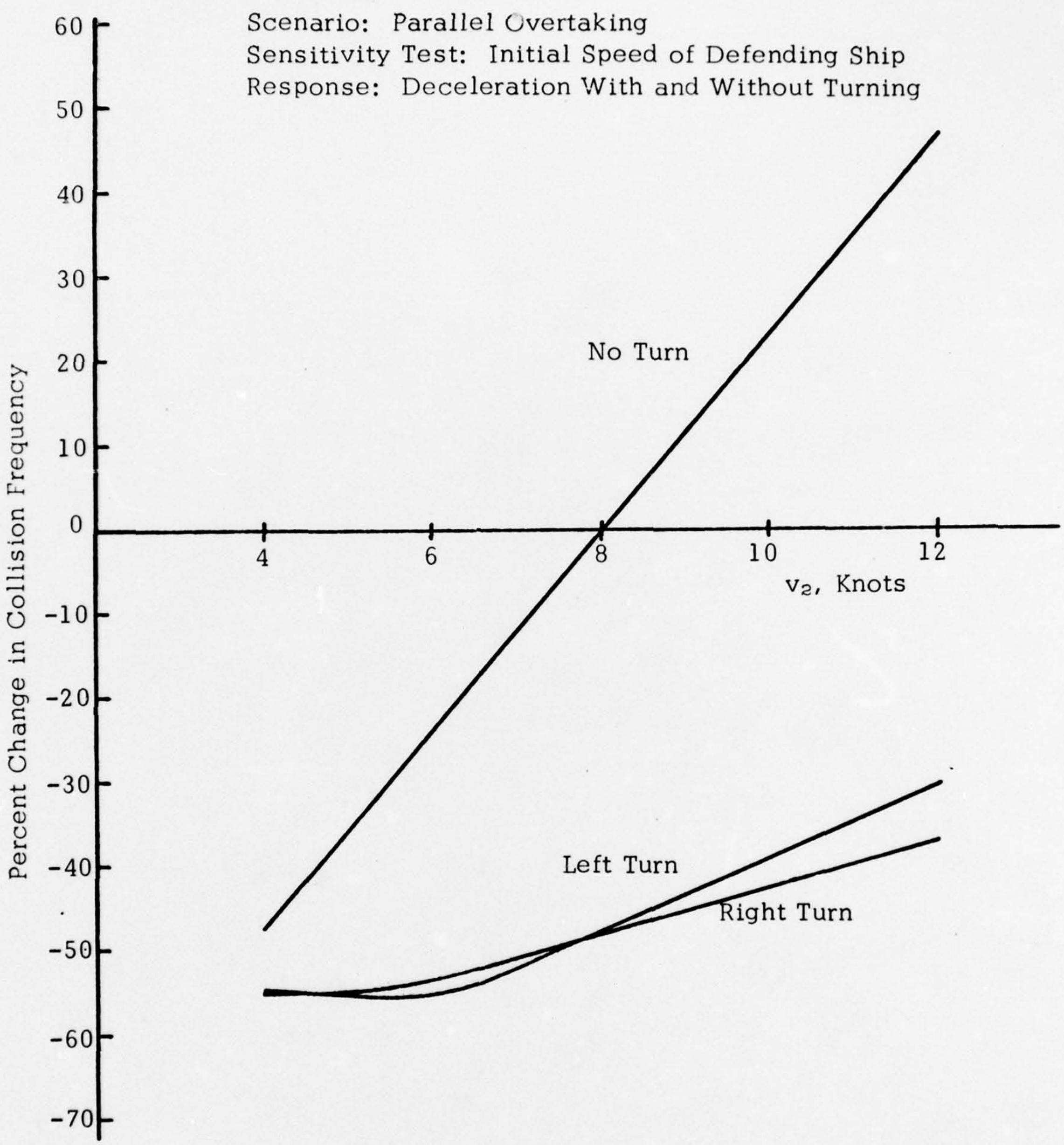

FIGURE 32. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

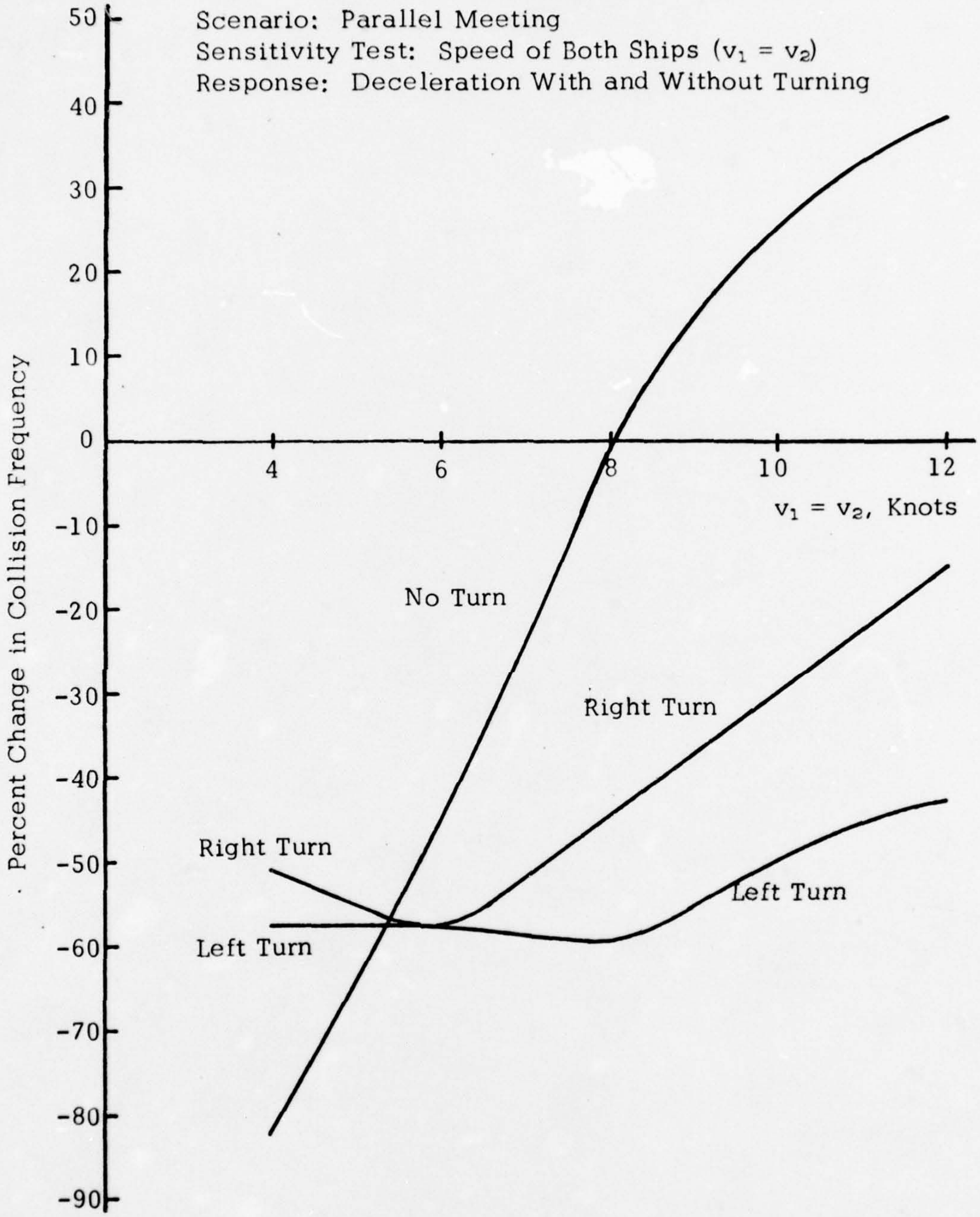

FIGURE 33. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

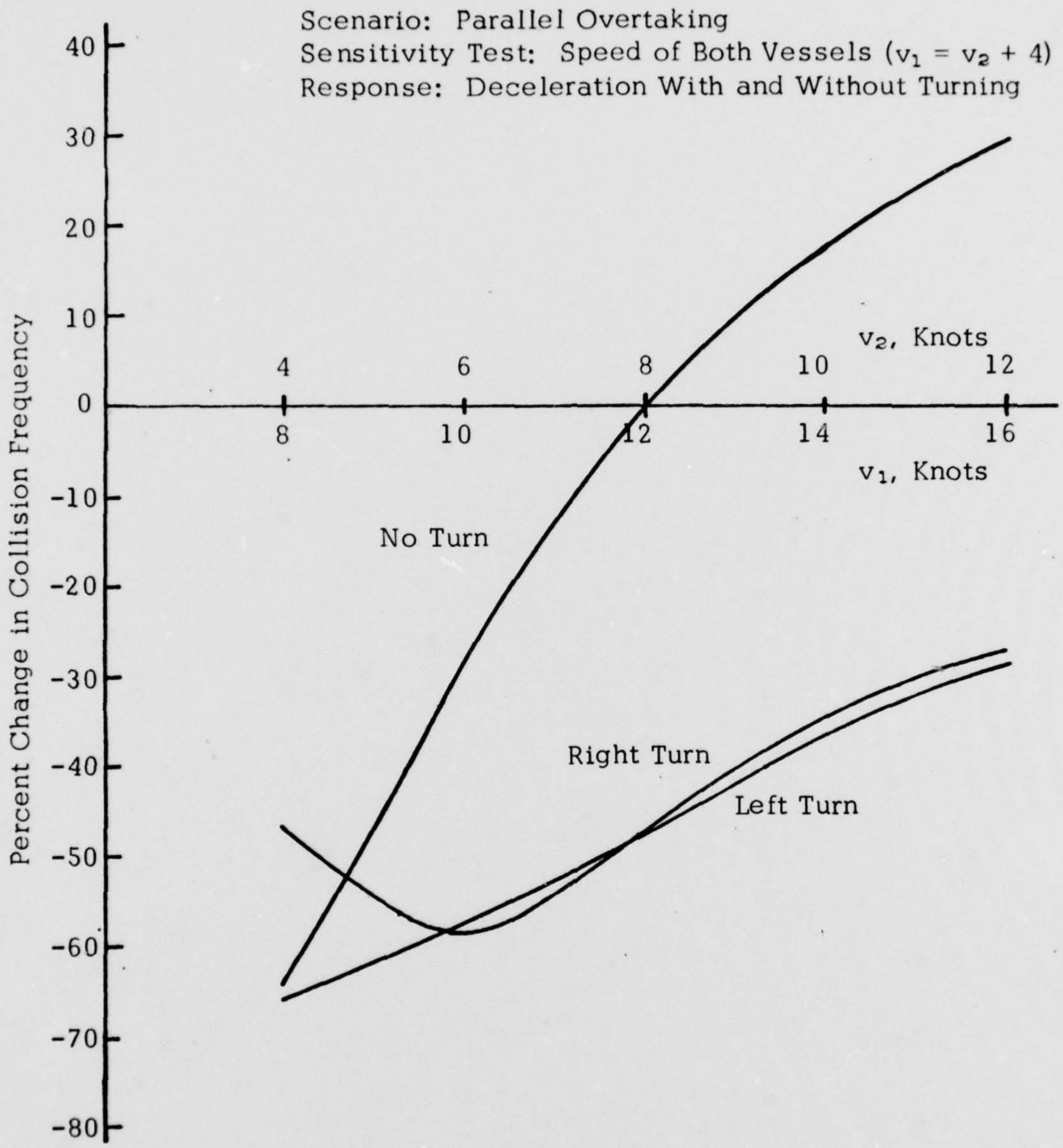

FIGURE 34. PERCENT CHANGE IN EXPECTED FREQUENCY OF COLLISIONS

TABLE 4

SENSITIVITY FINDINGS

System Parameter	Change in System Parameter Relative To Base Case	Percentage Change in Frequency of Collision: Meeting, No Turn	Meeting, Left Turn	Meeting, Right Turn	Overtaking, No Turn	Overtaking, Left Turn	Overtaking, Right Turn
Track separation	+ 50%	-22	-10	-15	- 5	- 5	- 5
Perception response, α_1	- 50%	-25	-14	-15	- 15	- 12	- 16
Deceleration time lag, α_2	- 50%	-11	- 6	- 6	- 10	- 9	- 9
Deceleration, ft/sec^2	+100%	-45	-10	-12	- 32	- 12	- 12
Maneuverability—both vessels							
Increased	B-60% R-30%	- 3	+ 2	+ 9	- 10	+ 17	+ 20
Decreased	B+60% R+30%	-45	-17	-26	- 29	- 30	- 35
Speed of erring ship	- 50%	-77	-93	-82	-100	-100	-100
Speed of defending ship	- 50%	-30	+ 8	+10	- 47	- 7	- 7
Speed of both	- 50%	-64	-47	-66	- 82	- 51	- 57

TABLE 5

BASELINE CASE
COMPARISON OF RESPONSE TO NO RESPONSE CASE

Scenario	Percentage Change in Frequency of Collision		
	Decelerate	Left Turn	Right Turn
Meeting	-38	-62	-58
Overtaking	-33	-65	-65

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the effect of each maneuver response in the baseline case compared to a no response situation. Table 6 shows the results of comparing the collision reduction potential of turning while decelerating to decelerating with no change in course.

Some brief comments on Tables 4 through 6 follow:

Table 4

1. Increasing track separation is two to four times more effective in avoiding collisions while meeting than in overtaking.

2. In the meeting scenario, quicker perception of a threat is more important when the response is simply decelerating than when a turn maneuver may be executed (i.e., alertness holds a higher premium in restricted waters than in more open areas where an evasive turn may be possible).

3. Deceleration time-lag is not a greatly influential system parameter.

4. In the meeting scenario, doubling the deceleration capability of the evading vessel cuts the collision rate almost in half for a no-turn response, but does little to reduce collision probability if the vessel is free to turn.

5. Improving the maneuverability of both vessels helps little, or slightly increases, the chance of collision. However, decreasing maneuverability of both ships helps somewhat (20 to 30 percent) in most cases, and more in the case of the no-turn response (45 percent). Reducing maneuverability results in a greater time requirement to cross the distance between the tracks and therefore gives the defending vessel more time to evade.

6. If the speed of the erring vessel is decreased by half, 80 percent or more of the collisions in the meeting scenario could be avoided and all collisions in the overtaking scenario could be avoided.

TABLE 6

COMPARISON OF DECELERATING WITH NO TURN VERSUS LEFT OR RIGHT TURN (OPPORTUNITY AND DECELERATION RESPONSE)

Scenario	Percentage Change in Frequency of Collision	
	Left Turn With Deceleration	Right Turn With Deceleration
Meeting	-60	-44
Overtaking	-47	-47

7. If, on the other hand, the speed of the defending (responding) vessel is decreased by half, probability of collision is reduced by 1/3 to 1/2 for the no-turn response; but the probability varies little when a turn response is made in a threat situation.

8. Decreasing the speed of both vessels in both the meeting and overtaking scenarios significantly reduces the expected frequency of collision from 50 percent to 80 percent.

Table 5

1. In the meeting and overtaking scenarios, a turn either way when decelerating is not quite twice as effective as deceleration with no turn.

Table 6

1. Given a deceleration response, it was computed that turning while decelerating decreases collision probability by half of the probability of simply decelerating.

Long-Range Crossing

A long-range crossing collision will not occur if the give-way (burdened) vessel observes the rules of the road. To analyze the effectiveness of collision-avoidance maneuvers, the model only considers maneuvers of the stand-on (privileged) vessel under the assumption that the give-way vessel does not in fact give way as it should.

Figure 35 is a scale drawing of the baseline case analysis of the long-range crossing scenario. Lines AA, BB, etc. illustrate the points along the path of the stand-on Vessel 2 at which the indicated maneuver must be executed in order to avoid collision should the give-way vessel fail to maneuver as required. The distance to CPA (where CPA = 0) and TCPA is shown as variable, depending on the angle of crossing. The response indicated allows Vessel 2 either to pass astern of Vessel 1 or not to cross its path at all.

Rudder cycling (line DD) and staying on a relatively constant heading is about twice as effective as simple deceleration (line EE). On the other hand, trying to come to a stop before the intersection of the vessel paths would have required starting to back at a range of three miles from CPA, or at a TCPA of about 23 minutes—far off the scale drawing. Avoiding crossing the path of Vessel 1 is indicated as better than any type of deceleration, but not as good of course as turning with the allowance of crossing the path. Lines BB and CC intersect as the headings become nearly reciprocal. This represents the fact that at a certain point the only safe right turn (aside from trying to cross ahead of Vessel 1) is simply not to cross the other ship's path.

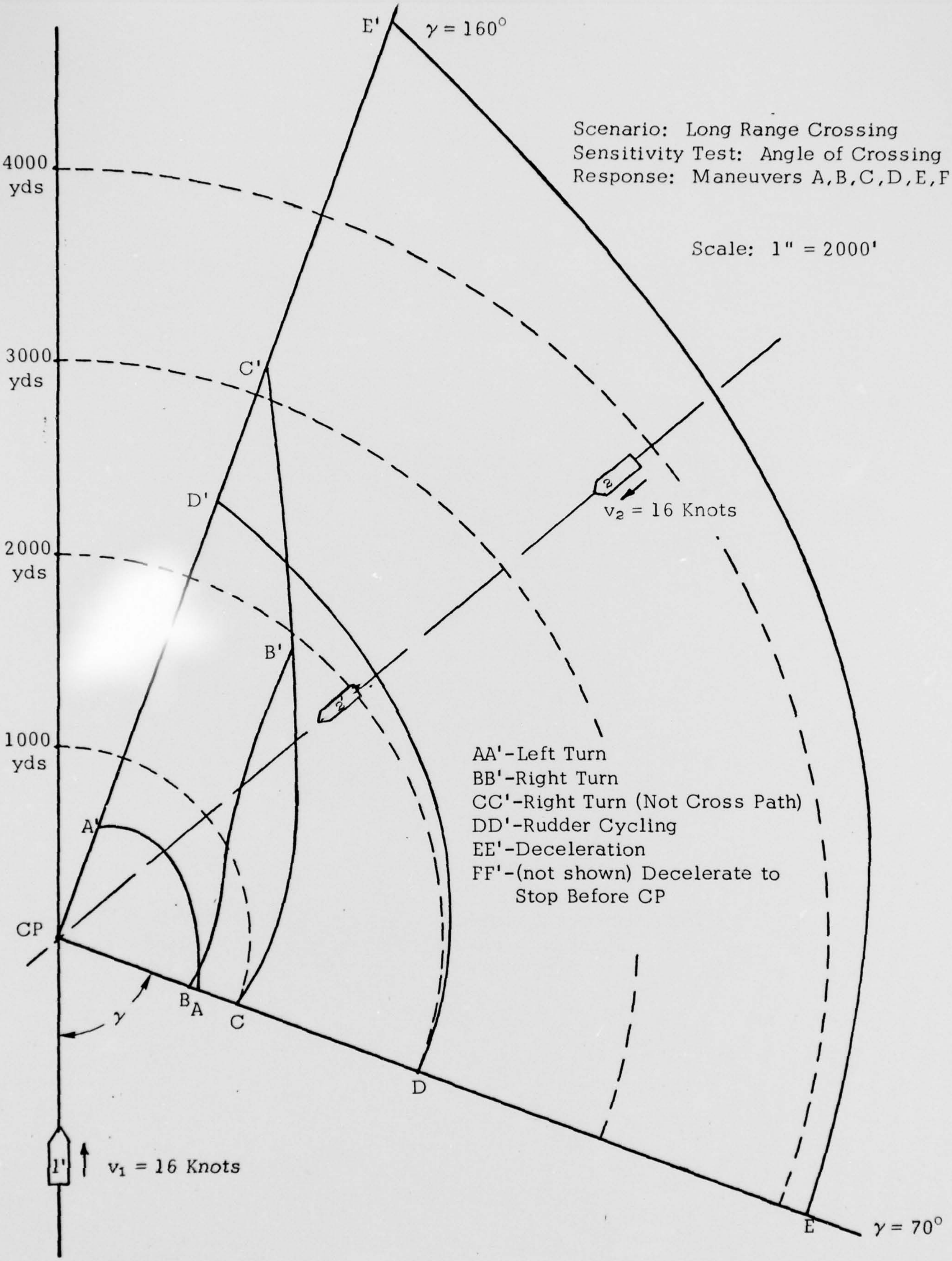

FIGURE 35. RANGE AT WHICH MANEUVER MUST BE INITIATED IN ORDER TO AVOID COLLISION

Head-On Meeting

In the head-on meeting scenario, both vessels are following the same track on reciprocal headings. In this situation neither vessel is privileged and a passing agreement must be reached. The usual manner of passing must be reached. The usual manner of passing is with both vessels altering course to starboard for a port-to-port passage. The assumption in the head-on meeting scenario is that Vessel 1 takes no action and does not respond to signals, and Vessel 2 (own ship) must finally take unilateral action to avoid an otherwise inevitable collision. In this situation the collision region is of infinite length—the question which must be answered is: "What is the minimum range and minimum time prior to collision (TCPA) that own ship can still initiate a maneuver to miss vessel 1 by at least 50 feet?"

Sensitivity analysis for the head-on scenario consists of working with two parameters—velocity and maneuverability. Figures 36 through 38 show the range and TCPA at which the responding vessel must initiate action in order to pass the other vessel with a safety margin of about 50 feet.

Figure 36 models the case in which the nonmaneuvering vessel is making a constant eight knots. The maneuvering vessel has velocity varying from 4 to 14 knots. The plots on the figure indicate the range and the TCPA at which the maneuver must be initiated.

In Figure 37, both velocities vary over the same range. In this instance, the range at maneuver is always the same because we are simply changing the speed at which the events occur.

Figure 38 indicates the differences under a variety of turning characteristics. As one would expect, the more maneuverable vessel would need much less time and distance to avoid collision.

ANALYSIS OF VARIANCE

In conducting a sensitivity analysis, it is the usual procedure to select a benchmark or "baseline case" as mentioned previously. Each of the parameters being studied is then systematically varied over some range (which includes its baseline case value), and the output is compared to the full baseline case situation to see what changes result. However, full and complete information about the effect of one parameter on system performance cannot be entirely specified since, when that parameter was being varied, all other parameters assumed a fixed value; therefore, the result from that sensitivity analysis is generally dependent on the other values which did not change. If, for instance, a different alpha was chosen for the baseline case, the result of changing the channel separation may be very different. This means that there is some functional dependence of channel separation on the alpha variable.

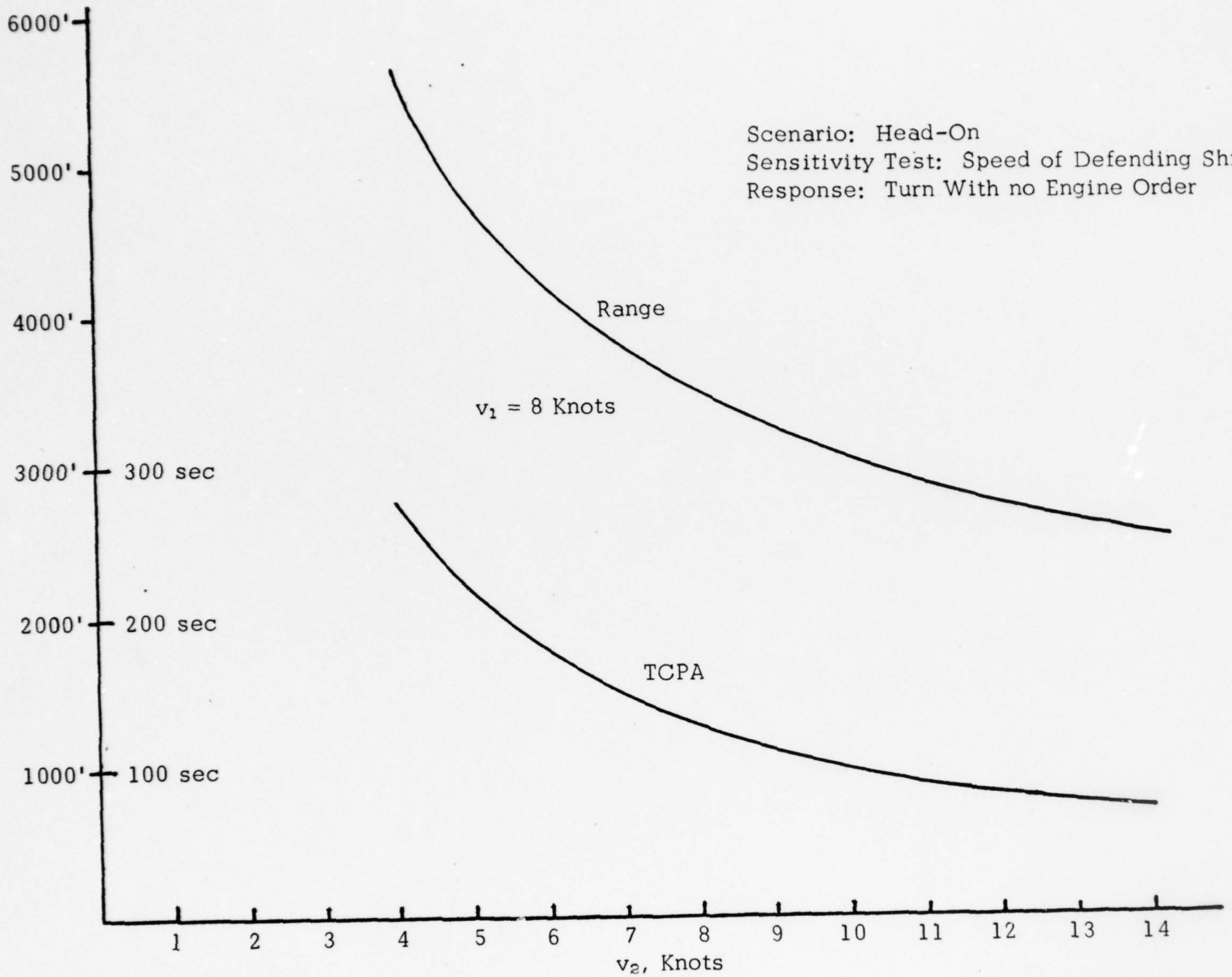

FIGURE 36. RANGE AND TCPA AT WHICH TURN MUST BE INITIATED TO AVOID COLLISION

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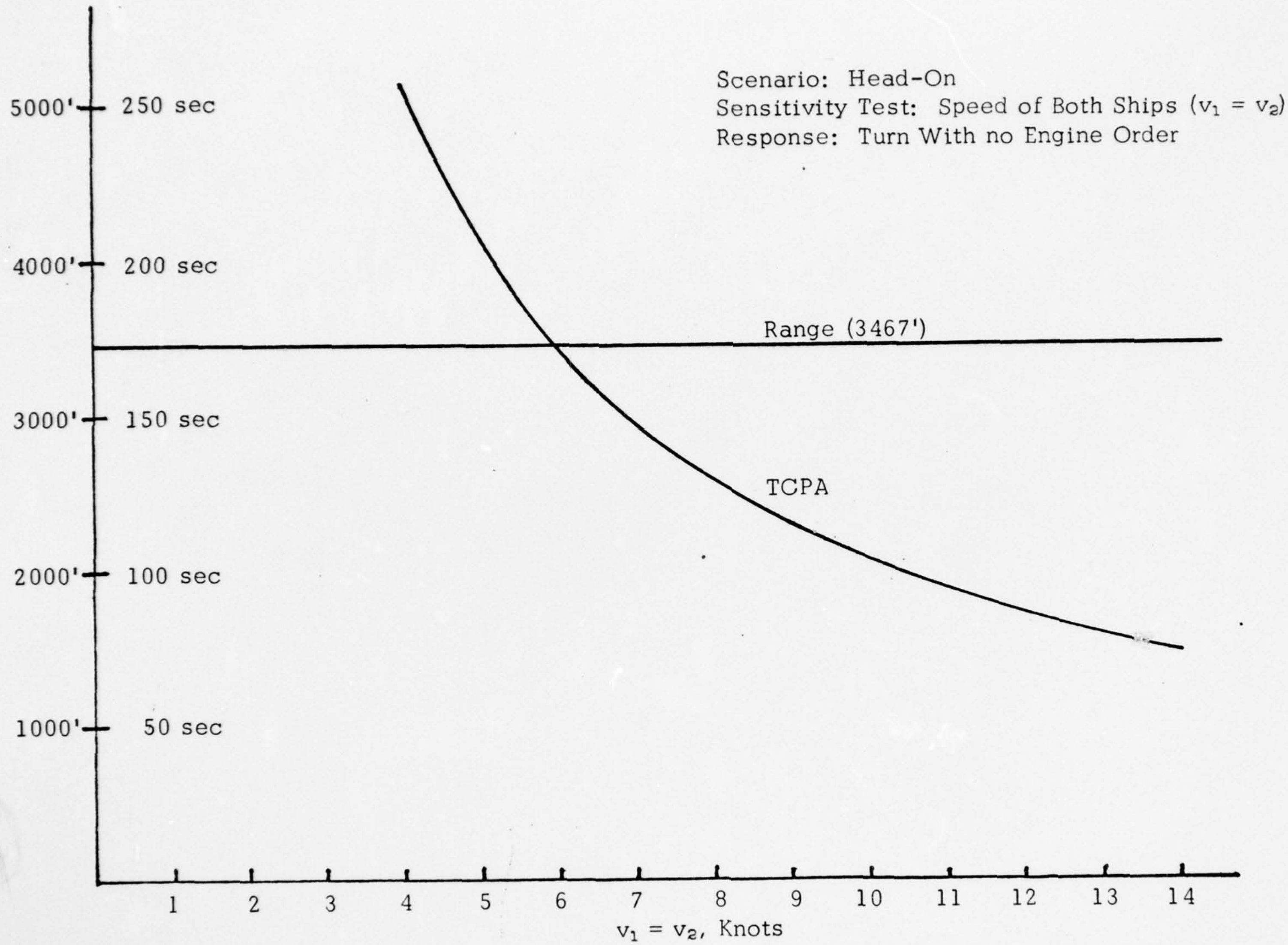

FIGURE 37. RANGE AND TCPA AT WHICH TURN TO AVOID COLLISION MUST BE INITIATED

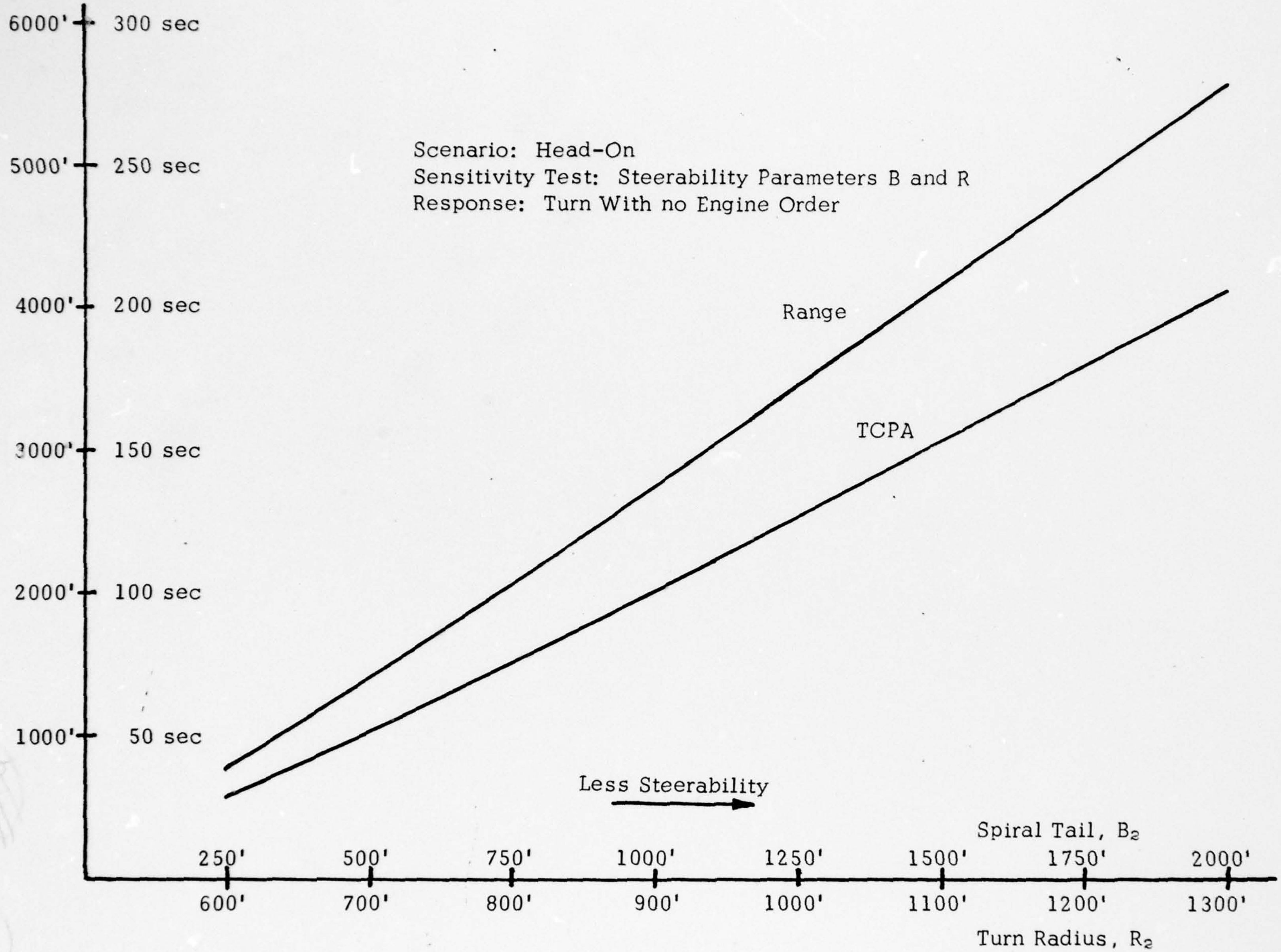

FIGURE 38. RANGE AND TCPA AT WHICH TURN MUST BE INITIATED TO AVOID COLLISION

In order to fully understand the nature of the variables in the maneuvering model, it would be necessary to conduct a statistical test known as Analysis of Variance to determine the interdependence between variables. In some cases, one parameter may change the expected number of collisions without regard to any other parameter values. In such a case, it would be appropriate to state that changing the parameter value will affect the likelihood of collisions no matter what the particular circumstances. However, it is more likely that affecting a system change like speed depends on such things as the kind of shipping being considered and the width of the channel being modeled.

The Analysis of Variance procedure would enable the model user to know more about the nature of the results he receives in a particular modeling exercise. This analysis would reveal the circumstances under which system change is advantageous and the circumstances in which it is unimportant.

Establishing a baseline case is, therefore, an excellent starting point. Since it facilitates understanding, for a given scenario, the operation and results of the given model. From that point, other situations can be modeled and the results may be interpreted separately, and then in relation to prior model runs. In this way, the full nature of the importance and impact of particular system changes can be discovered, at least in terms of the model of real-world activity.4/

4/ Hicks, Charles, R., Fundamental Concepts in the Design of Experiments, Holt, Rinehart, and Winston, New York, 1964, pp. 75-80.

217 216x

IV. COMPUTER PROGRAM

The mathematics of the maneuvering model have been translated into a FORTRAN computer program. This program is written in Level G, FORTRAN IV and has been run on an IBM 360/65 computer.

A generalized flow chart of the program is shown in Figure 2 of Section II. Figure 39 illustrates the logic for the parallel meeting and overtaking scenarios. These two scenarios are the most complex of the five which are considered in the model.

DATA INPUT REQUIREMENTS

There are four sections to the input deck for the program. All four are used for the parallel scenarios, but only the first three are required for the long-range crossing sudden appearance, and head-on scenarios. It should be noted at this point that, in the long-range crossing, sudden appearance and head-on scenarios, Ship 2 is always the ship whose response maneuvering capability is being tested.

Input Section I

This section consists of a single card on which the scenario, turn response, and engine order response is specified in three columns.

The Column 10 entry is an integer (1, 2, 3, 4, or 5) indicating the scenario:

1—Parallel meeting

2—Parallel overtaking

3—Long-range crossing

4—Sudden appearance

5—Head-on.

(519)

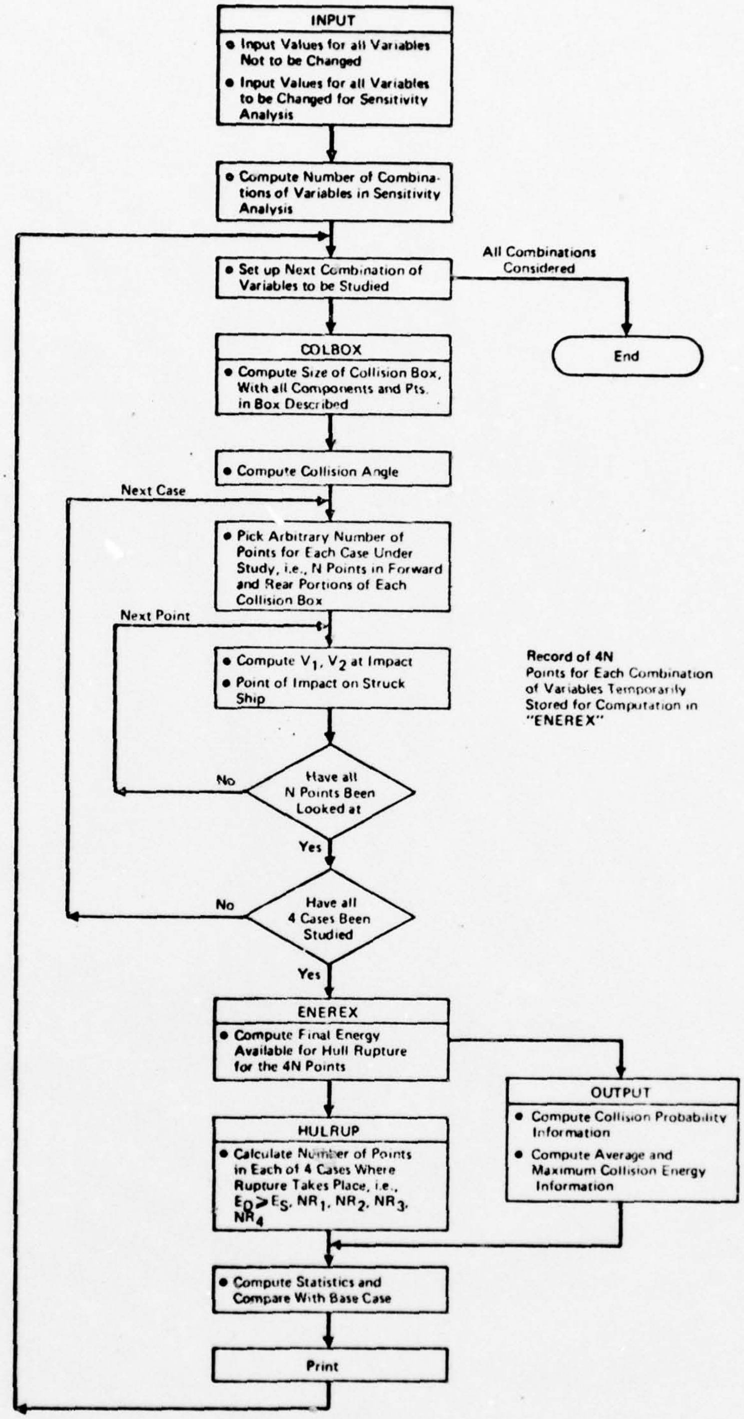

FIGURE 39. MANEUVERING MODEL LOGIC FLOW (PARALLEL SCENARIOS)

The Column 20 entry is an integer (1, 2, or 3) indicating the turn response:

1—No turn

2—Left turn

3—Right turn.

The Column 30 entry is an integer (1, 2, 3, 4, 5, or 6) indicating the engine order response:

1—No engine order

2—Appropriate use of deceleration

3—Appropriate use of acceleration

4—Appropriate use of deceleration or acceleration

5—Blind deceleration

6—Blind acceleration.

Figure 40 is an example of a data card.

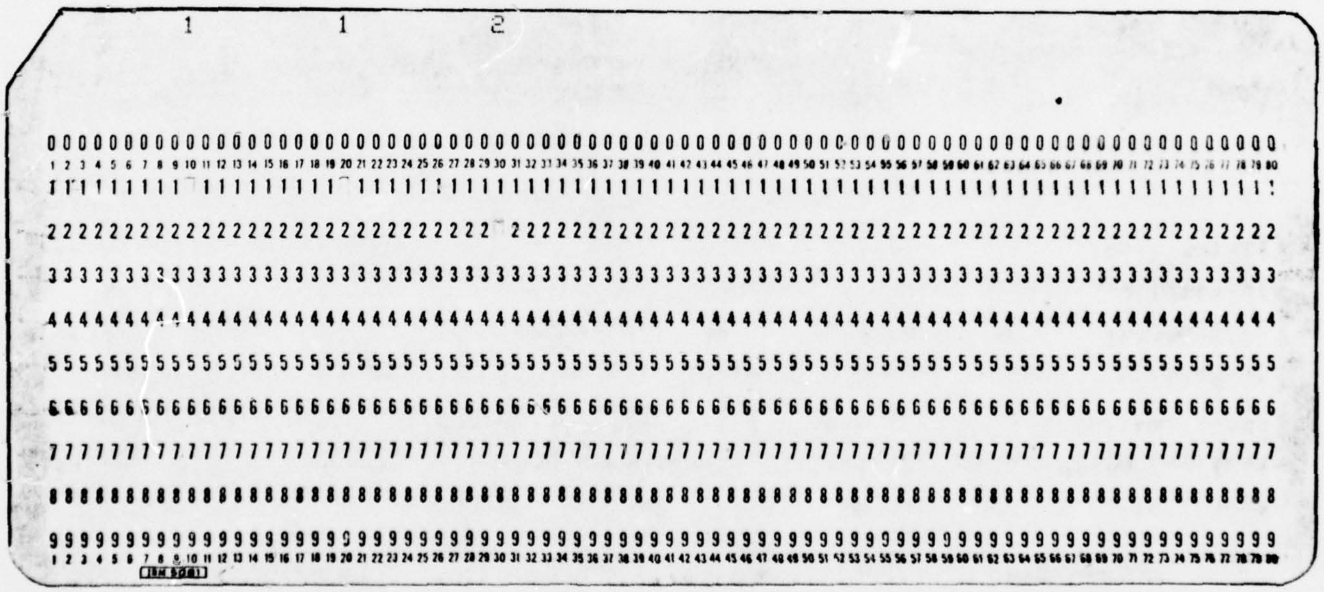

FIGURE 40. EXAMPLE OF SECTION I INPUT DATA CARD

Input Section II

This section contains a single card having eight fields of five characters each commencing with Columns 1, 6, 11, 16, 21, 26, 31 and 36. Right justification applies and placement of decimal point is of no concern as long as long as right justification is observed. Ship 1 data are entered in the first, third, fifth, and seventh fields.

Four pairs of ship data are read:

1—Crabbing angle, degrees into turn

2—Pivot point, decimal equivalent of fraction of ship length from bow

3—Transfer/steady-turn radius ratio, A/R

4—Ship width/length (beam to length ratio)

Figure 41 is an example of a data card.

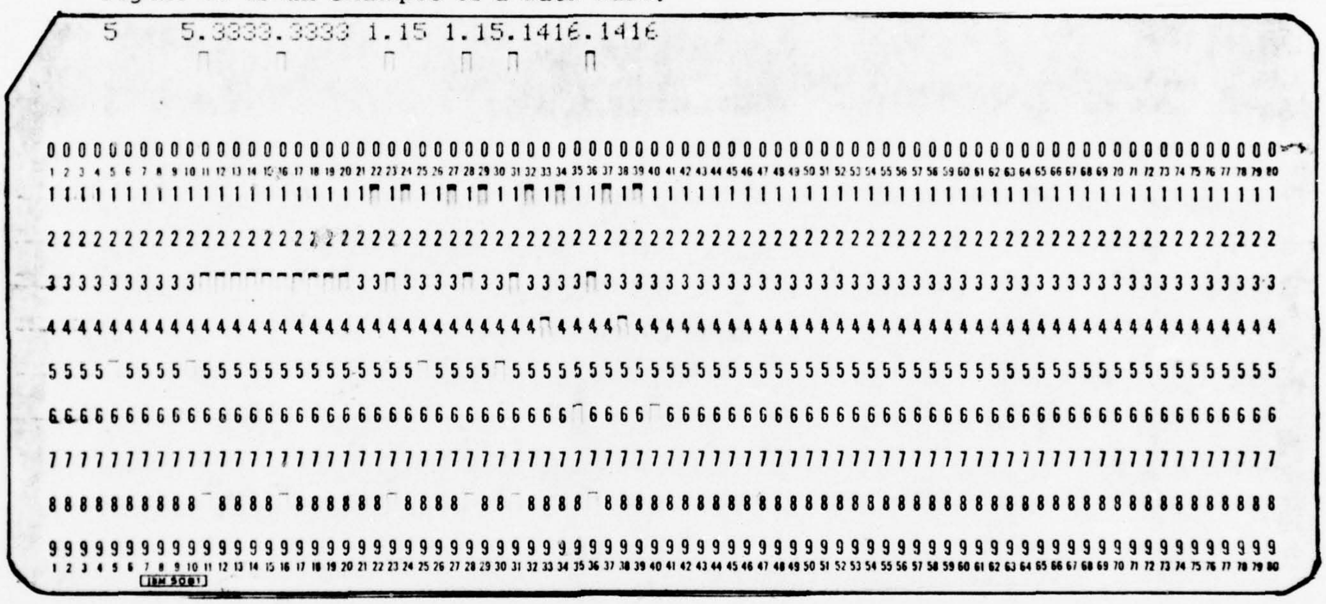

FIGURE 41. EXAMPLE OF SECTION II INPUT DATA CARD

Input Section III

This section contains 23 cards, one for each of 11 pairs of system parameters associated with the ships involved, plus one for track separation. The ordering of the cards is as follows:

Card Number	Parameter
1	Ship 2 displacement tonnage (long tons)
2	Ship 1 displacement tonnage (long tons)
3	Ship 2 length (ft)

Card Number	Parameter
4	Ship 1 length (ft)
5	Ship 2 hull rupture energy (ft lbs)
6	Ship 1 hull rupture energy (ft lbs)
7	Ship 2 time lag from Alpha 1 to initiation of response (sec)
8	Ship 1 time lag from Alpha 1 to initiation of response (sec)
	(Cards 7 and 8 concern an interim time delay between Alpha 1 and Alpha 2 which is currently not used. Field entries for these cards should be 1, 0, 1)
9	Ship 2 advance minus steady-state turn radius (B) (ft)
10	Ship 1 advance minus steady-state turn radius (B) (ft)
11	Ship 2 steady-state turn radius (R) (ft)
12	Ship 1 steady-state turn radius (R) (ft)
13	Ship 2 acceleration (ft/sec/sec)
14	Ship 1 acceleration (ft/sec/sec)
15	Ship 2 deceleration (ft/sec/sec)
16	Ship 1 deceleration (ft/sec/sec)
17	Ship 2 engine order time delay (Alpha 2) (sec)
18	Ship 1 engine order time delay (Alpha 2) (sec)
19	Ship 2 perception response (Alpha 1) (decimal fraction of track separation)
20	Ship 1 perception response (Alpha 1) (decimal fraction of track separation)
21	Channel track separation (ft)
22	Ship 2 initial velocity (knots)
23	Ship 1 initial velocity (knots)

Each card contains three fields of 10 characters each commencing with Columns 1, 11, and 21. Right justification is observed.

The first field contains an integer from 1 to 10. This field defines the number of parameter values to be used in sensitivity analyses.

The second field contains a real number which designates the smallest (or only) value of the parameter to be tested.

The third field contains a real number which indicates the incremental increase of the parameter value for this test.

Example. Card 22 shows entries of 5, 6 and 2 in its three fields. This indicates that, on this test, five values of initial velocity for Ship 2 are to be tested. The initial test will be made at six knots and each of the four succeeding tests will increase speed by two knots (i.e., 8, 10, 12, and 14 knots). Figure 42 illustrates a Channel Track Separation Card (Card No. 21) input for seven tests beginning with 400 feet and increasing 100 feet for each of the remaining six runs (i.e., 500, 600, 700, 800, 900 and 1,000).

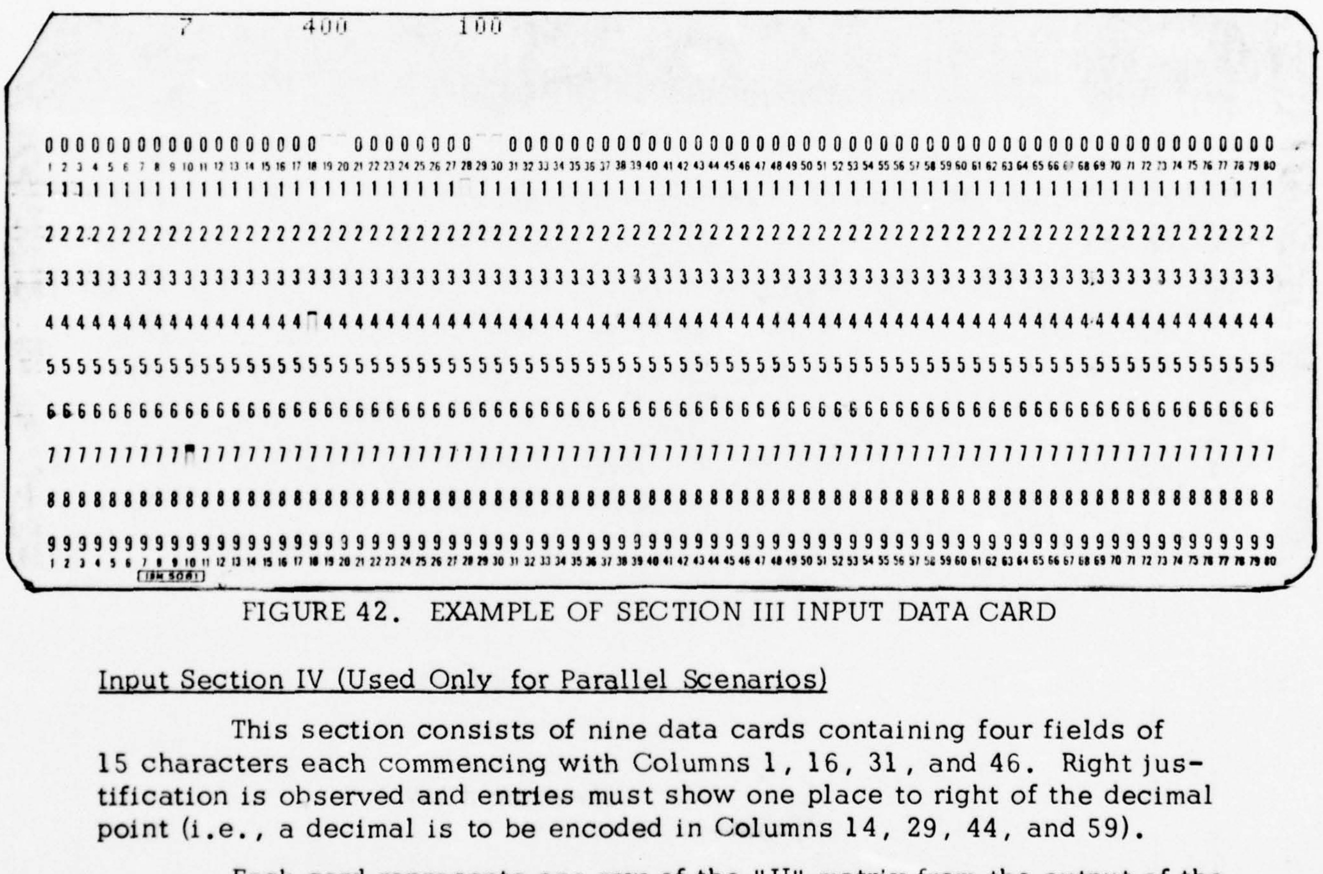

FIGURE 42. EXAMPLE OF SECTION III INPUT DATA CARD

Input Section IV (Used Only for Parallel Scenarios)

This section consists of nine data cards containing four fields of 15 characters each commencing with Columns 1, 16, 31, and 46. Right justification is observed and entries must show one place to right of the decimal point (i.e., a decimal is to be encoded in Columns 14, 29, 44, and 59).

Each card represents one row of the "U" matrix from the output of the model run which is being used as a base case for sensitivity analyses. An explanation of the contents of the "U" matrix is included in the listing under Subroutine OUTPUT. The information is used to produce the percentage change matrix of the output routine. The entries shown for the Input Section IV cards in Figure 43 are the base case values for the sensitivity analyses shown using the inputs from the cards illustrating Input Sections I, II and III. These are the same values defined for the base case in Section III of this report.

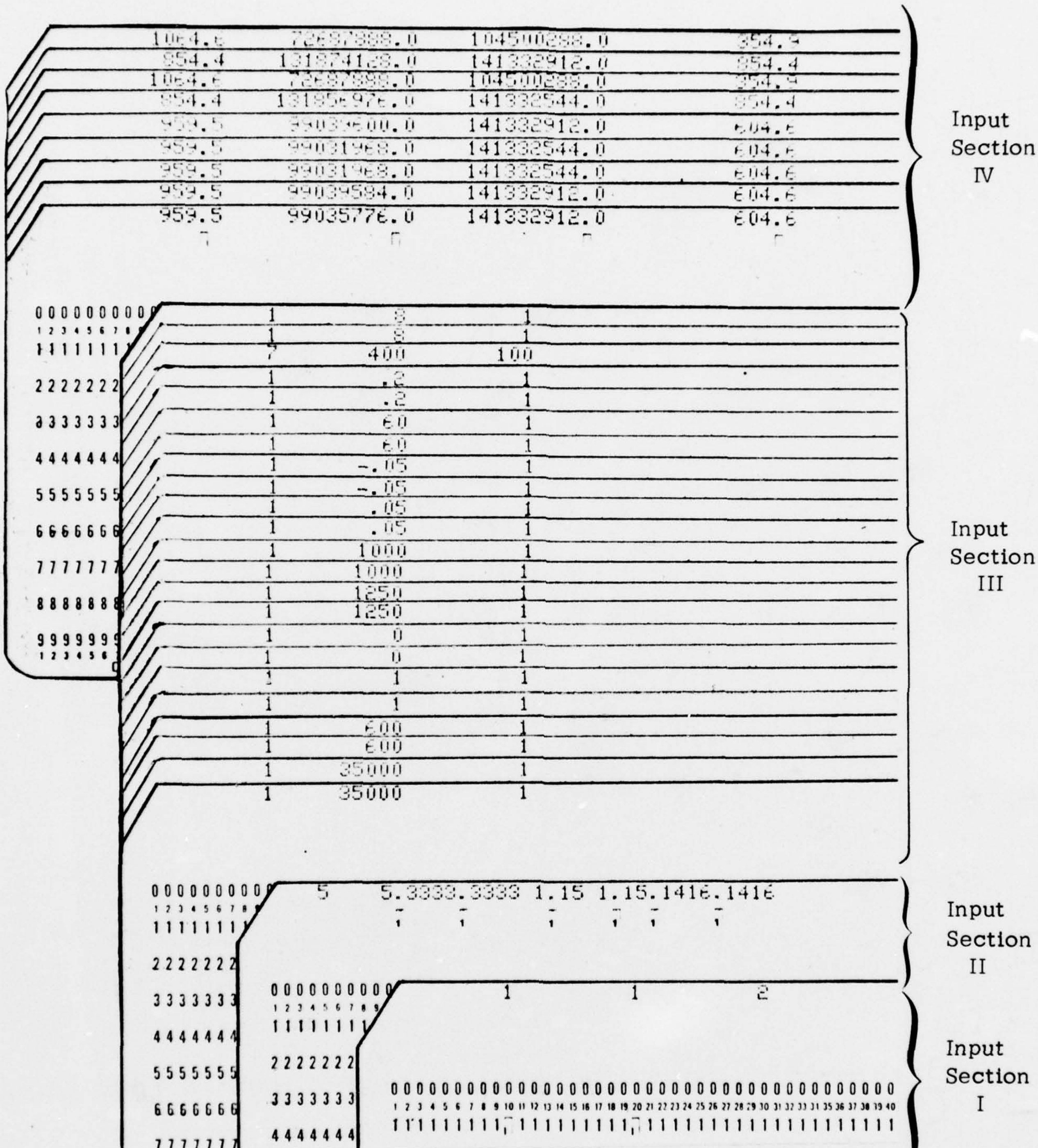

FIGURE 43. EXAMPLE OF A COMPLETE DATA DECK

Output Formats

The output contains the following information:

1. The scenario being modeled
2. The initial value of each system parameter
3. The value of the parameters in the sensitivity test for the run
4. The sensitivity test results.

Figure 44 shows an example of the output for the Parallel Scenarios and Figure 45 shows an example of the output for the Long Range Crossing and Sudden Appearance Scenarios. 1/

Program Listing

A complete program listing is included as Appendix I.

1/ Distances are in feet, time is in seconds, and bearing is in degrees off port bow.

U MATRIX - FOR USE IN PREPARATION OF BASELINE CASE DATA DECK

1	959.5	99035776.0	141332912.0	604.6
2	959.5	99039584.0	141332912.0	604.6
3	959.5	99031968.0	141332544.0	604.6
4	959.5	99031968.0	141332544.0	604.6
5	959.5	99039600.0	141332912.0	604.6
6	854.4	131856976.0	141332544.0	854.4
7	1064.6	72687888.0	104500288.0	354.9
8	854.4	131874128.0	141332912.0	854.4
9	1064.6	72687888.0	104500288.0	354.9

PERCENTAGE CHANGES

ERRING VESSEL	STRUCK VESSEL	PROB OF COLLISION	AVG COLL ENERGY	MAX COLL ENERGY	PROB OF RUPTURE
EITHER	EITHER	-0.0%	0.0%	0.0%	0.0%
EITHER	1	-0.0%	0.0%	0.0%	0.0%
EITHER	2	-0.0%	0.0%	0.0%	0.0%
1	EITHER	-0.0%	0.0%	0.0%	0.0%
2	EITHER	-0.0%	0.0%	0.0%	0.0%
1	2	-0.0%	0.0%	0.0%	-0.0%
1	1	-0.0%	0.0%	0.0%	-0.0%
2	1	-0.0%	0.0%	0.0%	-0.0%
2	2	-0.0%	0.0%	0.0%	-0.0%

FIGURE 44. OUTPUT FOR THE PARALLEL SCENARIOS

LEFT TURN RESPONSE

ANGLE	DISTANCE	TCPA	BEARING	RANGE
160,000	970,051	134.022	13,616	2981.799
150,000	953,144	126,677	19,978	2737,393
140,000	946,154	123,065	26,354	2577,115
130,000	943,275	120,957	32,767	2441,155
120,000	942,629	119,613	39,311	2310,114
110,000	943,475	118,720	45,964	2176,255
100,000	945,530	118,129	52,793	2036,331
90.000	948,752	117,764	59,059	1889,218
80,000	953,284	117,594	67,246	1734,987
70,000	959,480	117,616	75,070	1574,540

RIGHT TURN RESPONSE

ANGLE	DISTANCE	TCPA	BEARING	RANGE
160,000	1338,688	161,304	12,909	3706,708
150,000	1194,415	144.533	19,255	3201,987
140,000	1119,643	135,905	25,642	2901,387
130,000	1072.518	130,522	32,107	2673,451
120,000	1039,030	126,747	38,685	2475,033
110,000	1013,103	123,873	45,421	2288,347
100,000	991,612	121.539	52,358	2105,238
90,000	972,708	119,537	59,600	1921,985
80,000	955,115	117,729	67,223	1737,235
70,000	937,766	116,009	75,386	1551,166

NO TURN RESPONSE

ANGLE	DISTANCE	TCPA	BEARING	RANGE
160,000	2583,553	253,435	11,752	6156,699
150,000	2514.724	242,247	17,370	5706,595
140,000	2468,820	235,755	23.013	5430,434
130,000	2436,403	231,461	28,690	5135,754
120,000	2412,136	228,368	34,431	4839,363
110,000	2393,091	226,004	40,244	4530,391
100,000	2377,550	224,110	46,159	4204,020
90,000	2364,457	222,538	52,215	3858,705
80,000	2353,121	221,194	58,466	3494,680
70,000	2343,076	220,013	64,996	3113,418

RIGHT TURN NOT CROSSING PATH

ANGLE	DISTANCE	TCPA	BEARING	RANGE
160,000	2341,634	173,300	0,175	4612,031
150,000	2306,154	170,675	0.262	4455,027
140,000	2267,558	167,818	0,349	4261,473
130,000	2225.516	164,707	0.436	4035,846
120,000	2179,673	161,314	0,524	3775,135
110,000	2129,658	157,612	0,611	3488,853
100,000	2075,089	153,574	0,698	3179,048
90,000	2015,598	149,171	0,785	2850,321
80,000	1950,851	144,379	0,873	2507,812
70,000	1880,588	139,179	0,960	2157,183

FIGURE 45. OUTPUT FOR THE LONG-RANGE CROSSING AND SUDDEN APPEARANCE SCENARIOS

APPENDICES

Page

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APPENDIX A

BRIDGE-TO-BRIDGE RADIOTELEPHONE
QEM ANALYSIS DATA

This Appendix contains the Casualty Analysis Gauge used for the QEM analysis of Bridge-to-Bridge Radiotelephone effectiveness. The data sheets for Fiscal Years 1964-1967 which show the results of the QEM review based on a thirty percent random sample of ship collision reports during those years are available on request. The QEM review for Fiscal Years 1968-1974 was done as a part of previous analyses and the data sheets for those years are therefore not included in this Appendix.

CASUALTY ANALYSIS GAUGE FOR BRIDGE-TO-BRIDGE RADIOTELEPHONE IN ACHIEVING PASSING AGREEMENTS

In the review of casualty reports the following questions were answered. These questions comprise the gauge for this action:

1. Did one vessel detect the other, or did both vessels detect each other, at least a half mile apart? (If answer is NO, go to Question 5).

2. Did the vessels fail to establish two-way communication by bridge-to-bridge radiotelephone at a separation of a half mile or more?

3. Did both vessels have normal power and steering capability up to the time of collision? (Consider "suction" as a loss of steering capability.)

4. Were all environmental and human factor conditions normal and predictable (e.g., no unexpected gale winds, no unexpected strong currents) at all times when the vessels were separated by less than half a mile?

   (If Questions 2 through 4 have been answered, disregard 5 through 9.)

CASUALTY ANALYSIS GAUGE FOR BRIDGE-TO-BRIDGE RADIOTELEPHONE AS AN AID TO DETECTION OF HIDDEN TRAFFIC

The following questions were answered. These questions comprise the gauge for this action:

5. Did detection occur at less than a half mile?

6. Did the collision occur within a half mile of the center of the blind (vision-obstructing) bend or bridge?

7. Did the vessels fail to communicate their intentions before they were within a half mile of the center of the obstructing bend or bridge?

8. Did both vessels have normal power and steering up to the collision? (Consider suction as a loss of steering capability.)

9. Were environmental or human factor conditions predictable or similar to recent conditions?

10. Were both vessels of a type now required to have bridge-to-bridge radiotelephone?

11. Is the answer to either Question 2 or 7 the only NO answer in either the passing agreement or detection of hidden traffic series?

12. Would the collision have been preventable with the use of bridge-to-bridge radiotelephone?

APPENDIX B

COLLISION AVOIDANCE RADAR SYSTEM
QEM ANALYSIS DATA

This Appendix contains the Casualty Analysis Gauge used for the QEM analysis of the potential effectiveness of Collision Avoidance Radar Systems. The data sheets for Fiscal Years 1970-1974 which show the results of the QEM review based on all ship collision reports involving at least one ship of greater than 10,000 gross tons during those years are available on request.

CASUALTY ANALYSIS GAUGE FOR COLLISION AVOIDANCE SYSTEM QUASI-EXPERIMENT

This casualty analysis gauge was used in the reading of the five year (FY 1970-74) set of collision reports in which at least one of the involved vessels was 10,000 gross tons or larger and both were underway. All collisions of this type during that period were analyzed with this gauge to determine which might possibly have been prevented had a collision avoidance system of the MARAD approved type been employed on the vessels meeting the size requirement.

1. Was a lack of proper detection/evaluation of a collision threat by a vessel over 10,000 gross tons contribute to the cause of collision? If not skip all other questions except 16.

2. Did either ship lack normal propulsion and steering up to the time of collision? (Consider bank and other types of suction as a loss of steering).

3. Were there unusual environmental conditions which adversely affected ship controllability?

4. Were there any abnormal or unexplainable human actions which contributed to the collision?

5. Was the normal detection capability of radar impaired because of:

   a. A bridge structure?
   b. Land mass?
   c. Sea return?
   d. Rain?
   z. Other? (see remarks)

6. Would CPA and TCPA predictions have been inaccurate due to course changes by other vessel prior to the collision?

7. Did the radar system have a malfunction?

A "YES" TO ANY OF THE ABOVE QUESTIONS (2-7) MEANS INABILITY OF CAS RADAR TO AID IN COLLISION PREVENTION.

FOR SHIP(S) OVER 10,000 TONS:

8. Was the radar turned on?

9. Did anyone using the radar obtain accurate information prior to collision on the other vessel's:

   a. Presence?
   b. Range?
   c. Course and speed?
   d. CPA and TCPA?

10. Were accurate and timely plots of radar targets being made during the period prior to collision?

11. Did the conn officer have accurate information on the vessel's:

    a. Presence?
    b. Range?
    c. Course and speed?
    d. CPA and TCPA?

12. Would an audiovisual alarm have alerted inattentive watchstanders to the collision threat in time for corrective action?

13. Would CPA, TCPA, and target priority information provided by a CAS system have been useful in evaluating the situation better and lead to different collision avoidance actions?

14. Would a simulated maneuver feature have been useful in better evaluation of the maneuver alternatives and have led to different collision avoidance actions?

15. Would any of the following information have led to a better appreciation of the threat and resulted in a different course of collision avoidance action?

    a. Vessel size
    b. Vessel malfunction
    c. Hazardous cargo
    d. Rudder angle and engine order
    e. Target identification (for ease of (1) B2BRT communication and (2) radar tagging)

16. Might the collision have possibly been prevented with a MARAD approved radar CAS?

APPENDIX C

COLLISION CAUSES
QEM ANALYSIS DATA

This Appendix contains the Casualty Analysis Gauge used for the QEM analysis of collision causes. The data sheets for the two sample sets used in the review are available on request.

CASUALTY ANALYSIS GAUGE - COLLISION CAUSE

This Casualty Analysis Gauge for collision causes was used in the analysis of both the eleven year thirty percent random sample of all vessel casualty reports and in the five year set of all casualty reports involving collisions of two vessels underway wherein one of the ships displaced greater than 10,000 gross tons. The gauge is divided by subheadings into general categories for ease of reference. The numbering of questions and the alphabetizing of answers for those questions where a simple yes/no choice was insufficient for a complete analysis of the situation provide a key to the Quasi-Experimental results

EQUIPMENT FAILURES AND MALFUNCTIONS

1. Did either vessel suffer a steering failure which contributed to the collision?

2. Did either vessel suffer a propulsion failure which contributed to the collision?

3. Did either vessel suffer an interior communications equipment failure which contributed to the collision?

4. Did some other equipment failure contribute to the collision?
   - a. Cable break or parting
   - b. Radar malfunction
   - c. Radio malfunction
   - d. Navigational light malfunction
   - e. Whistle malfunction
   - z. Other (see remarks)

5. Was a back-up system available and operable, but not used? (If yes, see remarks)

RULES OF THE ROAD

6. Did the presence of a third vessel contribute to collision by:
   - a. Obscuring view?
   - b. Limiting maneuvering room?
   - c. Forcing the alteration of course or necessitating a less desirable maneuver to be made?
   - d. Leading to general confusion of intentions of other vessels?
   - z. Other (see remarks)

7. Was a misinterpretation of the Rules of the Road a contributing cause of the collision? (If yes, see remarks)

8. The scenario is classified as a:
   - a. Parallel meeting (PM) or Parallel meeting at a bend (PM,B)
   - b. Parallel overtaking (PO) or Parallel overtaking at a bend (PO,B)
   - c. Head-on meeting (HO) or Head-on meeting at a bend (HO,B)
   - d. Long range crossing (LRC)
   - e. Other (see remarks) (O)

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9. The Rules of the Road in effect were:

   a. International; Coastal, Harbor, or Other
   b. Inland; Harbor (If origin or destination for either vessel) or Other
   c. Great Lakes; Harbor (as defined above) or Other
   d. Western; Harbor (as defined above) or Other

VESSEL AND WATERWAY DESIGN

10. Did insufficient channel width contribute to the collision?

11. Did the collision occur at a bend in the waterway?

12. Did a channel obstruction contribute to the collision?

13. Was there a lack of vessel control due to:

   a. Insufficient power? (strong influence of current)
   b. Escessive freeboard? (strong influence of wind)
   c. Bank/bottom suction or cushion?
   d. Suction or cushion from other vessel?

14. Was there any other characteristic of the vessel design which significantly contributed to the collision? (If yes, see remarks)

15. Was there any other characteristic of the waterway which significantly contributed to the collision?

HUMAN FACTORS

16. Was one or more of the following Rules of the Road violated?

   a. Not posting or improperly posting a lookout
   b. Passing agreement
      1. Not attempting to get
      2. Proceeding without successfully attaining
   c. Whistle signals
      1. Not sounding fog signals
      2. Not sounding danger signal
      3. Not sounding bend signal
      4. Not sounding signal for permission to overtake and pass
      5. Not indicating initiation of maneuver (international waters)
      6. Not sounding or answering a request for a passing agreement
   d. Negligent maneuvering
      1. Not staying out of way of overtaken vessel
      2. Not staying/moving to correct or agreed upon side of channel
      3. Not moving to the right in a head and head meeting situation
      4. Not making proper and timely avoidance maneuvers in a dangerous situation or upon hearing a danger signal from another vessel
   e. Violating burdened/privileged rules when in a crossing situation under any of the Rules of the Road
   f. Excessive speed

g. Narrow channel rule
    1. Not staying right
    2. Not giving way to downbound vessel
h. Operating with defective equipment or in an unsafe condition
i. Operating without properly licensed personnel
j. Not monitoring bridge to bridge radiotelephone on correct frequency
z. Other (see remarks)

17. Was a navigational error, not a result of a misplaced or improperly operating navigational aid, a contributing cause of the collision? (If yes, see remarks)

18. Were any of the following errors in judgment made?

a. The position, course, speed of
    1. own vessel in a channel
    2. other vessel in a channel
    3. relationship to other vessel when in a long range crossing
b. The wrong assumption was made about the intentions of the other vessel
c. The planned maneuver was not feasible for the given vessels in the portion of the waterway where collision occurred
d. The effects of current or wind
e. An illogical maneuver was attenpted given the initial vessel courses and speeds
f. Passed other vessel closer than was necessary
g. Maneuvered closer to bank of waterway than was necessary
z. Other (see remarks)

19. At collision the period of the day and visibility were:

a. Day	a. less than ¼ mile
b. Night	b. ¼ to ½ mile
c. Twilight	c. ½ to 1 mile
	d. 1 to 2 miles
	e. 2 to 5 miles
	f. over 5 miles

20. Was late detection a contributing cause of collision due to:

a. Fog or smoke
b. A blind bend in the waterway
c. Bright shore lights obscuring navigational lights of other vessel
d. Insufficient or improper navigational lighting of vessel
e. Radar did not detect
f. Obstructing vessel, bridge, or other object
g. Inattention
h. Tow arrangement
i. Ice or condensation on windows
j. Cargo loaded so as to block vision
z. Other (see remarks)

21. Was a poorly given helm or rudder order a contributing cause of collision? (If yes, see remarks)

22. Was the helm or engine order not carried out properly (no equipment malfunction of any kind) ? (If yes, see remarks)

23. Did any other of the following human errors or failures occur?

a. Poor use of radar information
b. Inattention
c. Poor use of Bridge-to-Bridge Radiotelephone
d. Did not hear or misheard whistle signal
e. Did not use the whistle properly (not a violation)
f. Poor maneuvering of vessel
g. Inexperienced operator or lack of familiarity with waterway
z. Other (see remarks)

24. Was the vessel at fault in this collision underway for less than 12 hours?

25. Was the vessel at fault in this collision underway for more than 7 days?

26. Was the individual at fault near the end of his watch?

OTHER INFORMATION ABOUT THE COLLISION

27. Were any of the following environmental conditions a contributing cause of the collision?

a. Fog
b. Wind
c. Current
d. Smoke or haze
e. Rain or snow
z. Other (see remarks)

28. What was the total estimated damage resulting from the collision?

29. Was there any cargo on either vessel considered to be a hazardous or polluting substance?

a. Oil
b. Gas
c. Liquified Petroleum Gas
d. Chemicals
e. Diesel fuel
z. Other (see remarks)

30. The report of the casualty is:

a. Letter of Transmittal
b. Narrative
c. Marine Board

APPENDIX D

SAMPLE SHIP COLLISION REPORT

This appendix presents the Investigating Officer's memorandum filed with Coast Guard Casualty Report No. 20293 from Fiscal Year 1972. The complete record was reviewed in all three QEM analyses. The Investigating Officer's memorandum is presented to indicate the kinds of information available for the analyses; the casualty report form itself could not be clearly reproduced.

5943/C-4076
9 September 1971

FROM: Investigating Officer, MIO Juneau
TO: Commandant (MVI)
VIA: Commanding Officer, MIO Juneau/Commander, 17th CG District

SUBJ: FV SILVER SPRAY, O.N. 250538; collision with the Italian Passenger Vessel ITALIA, O.N. 242 in Stephens Passage, Alaska on 19 August 1971, without injury or loss of life

FINDINGS OF FACT

1. On 19 August 1971 at approximately 0210T the fishing vessel SILVER SPRAY and the Italian cruise ship ITALIA collided about .4 of a mile west of Portland Island, Stephens Passage, Alaska. There were no injuries or deaths but the SILVER SPRAY suffered extensive damage to her bow and port bow area. The ITALIA sustained a minor indentation on her port side, approximately 75 feet aft of the bow. The SILVER SPRAY arrived in Juneau, Alaska under her own power under Coast Guard escort at midmorning on 19 August 1971 while the ITALIA continued on her scheduled cruise.

2.

Name:	SILVER SPRAY	ITALIA
O.N.:	250538	242 (Italian)
Gross Tons:	73	12,218
Net Tons:	49	6,703
Length:	77.5'	491'
Breadth:	15.1'	70'
Depth:	7.8'	34.6'
Propulsion:	Diesel	Diesel (direct reversible)
Horsepower:	350	15,000
Homeport:	Juneau, Alaska	Cagliari, Italy
Owners/Operators:	William Carr P.O. Box 1606 Juneau, Alaska	Crociere d'Oltremara Flaminia 158/A Rome, Italy
Master:	Larry Hays Box 526 Douglas, Alaska	Giuseppe de Luyk %Princess Cruises 3435 Wilshire Blvd. Los Angeles, California
License:	None	Master-Oceans Issued by Italian Government
Pilot:	None	A.H. Clough 747 Gold Belt Ave. Juneau, Alaska

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9 September 1971

Subj: FV SILVER SPRAY, O.N. 250538; collision with the Italian Passenger Vessel ITALIA, O.N. 242 in Stephens Passage, Alaska on 19 August 1971 without injury or loss of life

License:	None	Alaska State License #0035 Coast Guard #242072, 1st Class Pilot, waters of SE Alaska, any gross tons
Certificate:	None	Z-1254813
Last Inspected:	Uninspected	10 December 1970 (Control Verification Cert.) Endorsed: 4 Jun 71, Los Angeles, Calif.

3. The weather in the area and at the time of the casualty was: scattered rain, overcast, visibility 5-10 miles, winds northeasterly at about 15 knots, air temperature about 50°. Sea conditions were: slight chop, height about one foot, no swell and water temperature in the upper 40's.

4. The ITALIA, with pilot Clough aboard, on the bridge, departed Juneau at midnight on the 18th of August 1971 enroute Skagway, Alaska. Aboard were 414 passengers and this was her last cruise in Alaskan waters for the season. At about 0030T on the 19th, she had cleared the harbor and reached cruising speed of 145 RPM (17.5 knots). Clearing the southern end of Douglas Island, she set course northerly up Stephens Passage. At about 0155T, on course 328°T the ITALIA, with Clough and the Second Mate Mario Ienco on watch observed a target on radar at a range of five miles bearing approximately 10° on the port bow. A single light was visible on this bearing, of undetermined color. The ITALIA was allowed to drift to course 330T as the target drifted aft.

5. At a range of about a mile, the light was determined to be green, with no other lights noticeably visible on the target. Shortly thereafter, the bearing stabilized and at approximately 0207T the ITALIA sounded one blast on the ship's whistle. The vessels continued to close and at 0209T the ITALIA sounded four blasts and Clough rang up "all stop" on her engines. About a minute later, the SILVER SPRAY became visible in the glow of the ITALIA's forward range lights, heading on an easterly course, perpenticular to the course of the ITALIA. At 0210 1/2T, the vessels collided with the SILVER SPRAY striking the ITALIA about 75' from her bow down the port side. The SILVER SPRAY hit on her port bow. The helm of the ITALIA was put hard to port to clear the SILVER SPRAY and then she maneuvered in close to assist. Communications were established between the vessels and the Coast Guard Rescue Coordination Center in Juneau, Alaska. The SILVER SPRAY declined assistance from the ITALIA, indicating

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there were no injuries and the SILVER SPRAY was not taking on water. At about 0315T, the owner and master of the SILVER SPRAY released the ITALIA and she continued on her way to Skagway.

6. The FV SILVER SPRAY (ex-CG80307) is used as a packer, buying fish at various points in SE Alaska. At 1530T on 18 August 1971 she departed Inian Island, Alaska where she had spent the previous five days buying fish. On board were the master and two crew members plus the owner, his wife and daughter.

7. Sometime shortly after midnight on 18 August 1971, the SILVER SPRAY was traversing Saginaw Channel enroute Juneau. At approximately 0155T on 19 August crewmember Dave Hunt relieved Dan Hunt of the wheel, having just been awakened. Dave Hunt had just had about two hours sleep after having been up working since 0800T on the 18th. The master Larry Hays, was asleep on the deck of the bridge. At the time of relief, a course was being made in line from Favorite Reef to Middle Point (120^{o}-130^{o}). Both Dan and Dave Hunt (brothers) indicated that they were watching the ITALIA. The SILVER SPRAY was making 5-6 knots, not going fast as capable due to an overheating engine.

8. At a distance of about 100 yards from the ITALIA, Dave Hunt woke the master and asked "which side would the red light be on?" and about this time, one blast was heard from the ITALIA. It was not answered. Hays, the master, took the wheel and turned hard to port. At about that time, multiple blasts were heard from the ITALIA. Hays backed hard astern and simultaneously, the vessels collided.

9. The SILVER SPRAY struck the ITALIA at an angle of about 15^{o} off her port bow, hitting the ITALIA about 75 feet aft of the bow. Immediate investigation indicated that none of the persons on board were injured and that the SILVER SPRAY was not taking on water. Communications were established and after deciding they they could make Juneau under their own power and upon receiving assurance that a Coast Guard vessel was enroute, the owner and the master of the SILVER SPRAY advised the ITALIA that their assistance was not needed.

10. At about 0530T, the CGC CAPE CORAL met the SILVER SPRAY and commenced escorting her to Juneau. At about 0740T the CAPE CORAL placed two pumps and three men aboard the SILVER SPRAY to remove water which the boat had started taking on. A six inch hole was found and plugged, and the boat dewatered. At 0915T the SILVER SPRAY docked at the Cold Storage Dock in Juneau and off-loaded her cargo. She then shifted to Aurora Basin, where she was moored and left unattended.

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11. On 30 August, the Coast Guard was required to assist the SILVER SPRAY in dewatering when it was found that she was taking on water. The owner subsequently placed portable pumps on board in the event of reoccurrence. The SILVER SPRAY has not been repaired to date, but is considered repairable. Damages include the stern being broken from slightly below the waterline to the forepart, the hull timbers, etc., being demolished at least a distance of 20 feet from the bow and foredeck in the area torn and raised, with a portion of the starboard bow cracked and requiring replacement.

12. The master of the SILVER SPRAY has five years experience operating vessels in Alaska and the wheelwatch, Dave Hunt, has indicated approximately 2-1/2 years experience on boats in Alaska. Both men, when questioned by the investigating officer, indicated that they "were not sure of the signals" as required by the Inland Rules of the Road.

CONCLUSIONS

1. It is concluded that this casualty was caused by the failure of the burdened vessel to yield the right of way in a crossing situation, though there was no apparent need for the situation to exist.

2. That, there is evidence of violation of law in that the operator of the SILVER SPRAY failed to keep a close watch on an approaching vessel; failed to keep clear in a crossing situation; and failed to sound whistle signals as required by the Inland Rules of the Road. A report of violation has been submitted concerning these alleged violations.

3. That, there is evidence of negligence in violation of regulations in that the SILVER SPRAY was being operated by personnel not familiar with the Inland Rules of the Road. A report of violation has been submitted concerning this alleged violation.

4. That, the ITALIA maintained her course and speed as required by the Rules of the Road and had she changed her course to port, the danger of collision would have greatly increased and had she changed her course to starboard, the vessel, crew and passengers would have been greatly endangered due to the close proximity of Portland Island.

5. That, there is no evidence of actionable negligence, misconduct, inattention to duty or violation of any law or regulation on the part of any licensed or certificated person; that, there is no evidence that any person of the Coast Guard or any other governmental agency contributed to this casualty; and that no aids to navigation were involved in this casualty.

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6. That, had the SILVER SPRAY maintained course and speed and had not the master made a course change to port, that this casualty would not have occurred.

RECOMMENDATIONS

1. It is recommended that, inasmuch as a Report of Violation has been submitted covering the alleged violations of law and regulations, that no further action be taken and that the case be closed.

/s/
F. E. TAYLOR

Encl: (1) CG-2692, ITALIA
(2) CG-2692, SILVER SPRAY
(3) Chart of ITALIA's course
(4) Chart of SILVER SPRAY's course

m
10 September 1971

FIRST ENDORSEMENT

From: Commanding Officer, MIO Juneau/Commander, 17th CG District
To: Commandant (MVI)

1. Forwarded approved. No further action is indicated in this instance.

2. The question arises whether the ITALIA took sufficient action to avoid collision once the situation became "in extremis." It is my opinion that she did. There was every indication that the smaller vessel would pass safely to port and she would have done so had not her master turned to port on awakening, rather than making a normal turn to starboard.

3. Penalty action is being taken against the master and the owner of the SILVER SPRAY under the Administrative Procedures Act.

/s/
A. A. FONTAINE
By direction

APPENDIX E

CONFIDENCE LIMITS FOR ESTIMATING PROPORTIONS IN A FINITE POPULATION FROM A 30 PERCENT RANDOM SAMPLE

The following methods were used in the determination of confidence limits in all analyses using the 30 percent random sample of all underway collisions. A binomial distribution is assumed.

Derivation of confidence limits for estimating population proportion of successes (p) when the population is finite (N_p) and the random sample is of size $N = kN_p$, $0 < k < 1$. The sample proportion P in standard units is:

$$\frac{P - p}{\sigma_p} = \frac{P - p}{\sqrt{\frac{p\,(1-p)}{N}}\ \sqrt{\frac{N_p - N}{N_p - 1}}} \quad . \tag{E.1}$$

If we replace $N_p - 1$ by N_p, this can be written approximately as:

$$\frac{P - p}{\sqrt{\frac{p\,(1-p)}{N}} \cdot \sqrt{1 - \frac{N}{N_p}}} \tag{E.2}$$

or

$$\frac{P - p}{\sqrt{\frac{p\,(1-p)}{N}} \cdot \sqrt{1 - k}} \quad . \tag{E.3}$$

In our case we have a 30 percent random sample, so $k = .3$ and $\sqrt{1 - k} = .84$.

The largest and smallest values of the standardized variable are $\pm Z_c$ where Z_c determines the level of confidence. At these extreme values we must therefore have:

$$\frac{P - p}{.84\sqrt{\frac{p\,(1-p)}{N}}} = \pm Z_c. \tag{E.4}$$

Squaring both sides, we have

$$P^2 - 2pP + p^2 = .7Z_c^2 \; \frac{p\,(1-p)}{N} \tag{E.5}$$

or

$$(N + .7Z_c^2)\, p^2 - (2NP + .7Z_c^2)\, p + NP^2 = 0. \tag{E.6}$$

Solving for p, we get

$$p = \frac{P + .7\,\frac{Z_c^{\,2}}{2N} \pm .84Z_c\sqrt{\frac{P(1-P)}{N} + \frac{.7Z_c^{\,2}}{4N^2}}}{1 + \frac{.7Z_c^{\,2}}{N}}. \tag{E.7}$$

References:

1. S. S. Wilks, Elementary Statistical Analysis, Princeton University Press, 1958, p. 202.

2. M. R. Spiegel, Theory and Problems of Statistics, Schaum Publishing Co., 1961, p. 163.

APPENDIX F

DESCRIPTION OF THE COLLISION AVOIDANCE RADAR SYSTEM*

"A collision avoidance system designed as a supplement to both surface search navigational radars, via interswitching, shall be installed. The system shall provide unattended monitoring of all radar echoes and automatic audio and visual alarm signals that will alert the watch officer of a possible threat. The display shall be contained within a console capable of being installed adjacent to the radar displays in the wheelhouse and may form a part of the bridge console.

"Provision for signal input from the ship's radars, gyro compass, and speed log, without modification to these equipments shall be made. The collision avoidance system, whether operating normally or having failed, must not introduce any spurious signals or otherwise degrade the performance of the radars, the gyro compass or the speed log.

"Computer generated display data for each acquired target shall be in the form of a line or vector indicating true or relative target course, speed and both present and extrapolated future positions. Data shall be automatically displayed on a cathode ray tube or other suitable display contrivance sufficiently bright and unobstructed to permit viewing by more than one person at a time.

"In addition to displaying the collision potential of the most threatening fixed and moving targets, the system shall be capable of simultaneously showing land masses.

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* Maritime Subsidy Board, Maritime Administration, "Standard Specification for Merchant Ship Construction," Federal Register, Vol. 40, No. 144, P. 31250, Friday, July 25, 1975. Also; Section 9A, Article 4(4), Collision Avoidance System.

"The system display shall include a heading indication and bearing ring. The system shall also have the capability of allowing the operator to select "head-up" and "north-up" mode and to cancel the vector or line presentation of any of the targets. The presentation shall be non-smearing when changing modes or display scales in order to permit rapid evaluation of the displayed data.

"Target acquisition, for display data purposes, may be manual, automatic or both as specified by Owner.

"For any manual acquisition system the alarms shall be initiated by a preset minimum range; and likewise for any automatic acquisition system the alarms shall be initiated by a preset minimum acceptable passing distance (CPA-Closest point of approach) and a preset advance warning time (TCPA - Time to closest point of approach). Means shall be provided to silence the audio alarm for a given threat but the alarm shall resound upon a subsequent threat. The visual alarm shall continue to operate until all threats have been eliminated. If the collision avoidance system fails to perform as indicated above, after the system is set for unattended monitoring, the system shall produce both audio and visual warning alarms.

"The system shall be capable of simulating a trial maneuver.

"In addition to the target display, an alphanumeric readout shall be provided which can present range, bearing, course, speed, CPA and TCPA for any selected target, either on the target display or by other display means.

"The collision avoidance system shall be energized from the interior communications panel board in the Wheelhouse.

"The collision avoidance function may be incorporated in an integrated conning system, provided that failure of any other integrated system component will not degrade the collision avoidance function."

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APPENDIX G

FEASIBILITY OF USING A LOGIC TREE METHODOLOGY IN REPORTING MARINE ACCIDENTS

This appendix was originally published as ORI Technical Memorandum 110-76 (W.C. Rogers, June 23, 1976).

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I. INTRODUCTION

BACKGROUND

In support of the USCG spill risk analysis program, ORI found it useful to construct a Safety Analysis Logic Tree (SALT).[1] This logic diagram (the SALT) was constructed in order to examine and characterize the structural relationships within various collision scenarios.

The SALT was built specifically to develop a set of questions which could be answered yes or no, called a Casualty Analysis Gauge (CAG).[2] The CAG is specifically designed to answer a given problem statement using a logical set of criteria which tend to eliminate judgmental factors which so often intrude in the analysis of narrative data.

During the formal review of ORI's work, an observation was made that the SALT method embodies a formalization which might be of assistance in accident investigation and reporting. It was believed that some sort of a general formalization which would aid the accident investigator is feasible,[3] and specific improvements in the accident reporting system have long been sought.[4]

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1 Spill Risk Analysis Program, Phase II, Methodology Development and Demonstration, ORI Technical Report 840, Appendix F, June 1974.

2 Spill Risk Analysis Program, Methodology Development and Demonstration, Vol. 1, ORI Technical Report 964 (draft), p. 17, October 1975.

3 Ludwig Benner, Jr., "Accident Investigations: Multilinear Events Sequencing Methods," Journal of Safety Research, Vol. 7, No. 2, June 1975.

4 Battelle Columbus Laboratories, The Development of an Interactive Computer Program to Analyze Vessel Casualty Information, Vol. 1, June 1974, prepared for U.S. Coast Guard, and National Archives and Record Service (NARS), An Improved Vessel Casualty Reporting System, November 1975, prepared for U.S. Coast Guard.

PURPOSE

The purpose of this report is to evaluate the usefulness of using the Safety Analysis Logic Tree (SALT) methodology in both marine casualty and pollution incident reporting systems. The usefulness will be judged primarily by its ability to produce quantitative measures of effectiveness from input data which can be efficiently collected. In other words, the basic question is, "Will a SALT-type methodology produce an accident model which gives useful outputs from easily collectable data?" If it will, then it is expected that the method will have the following attributes:

1. It will aid in accident investigation.
2. It will increase the ease and accuracy in accident reporting.
3. It will increase the efficiency of recordkeeping and data retrieval.
4. It will increase the efficiency in information retrieval (that is, generation of measures of effectiveness).

SCOPE

The scope of this effort was limited to an assessment of the feasibility of such an approach to accident modeling. Accident modeling is meant to include investigation, reporting, recordkeeping, and measuring system effectiveness. The assessment addresses specifically the following four items:

1. What is the problem with current accident modeling (including investigation, reporting, recordkeeping, and measuring system effectiveness)?
2. What is known about the use of a SALT-type model?
3. What remains to be worked out for a SALT-type model?
4. How should such a SALT-type model be evolved?

BROADENING OF SCOPE

Because of the very limited nature of this study (approximately 3 man-weeks), there was a desire to limit the study strictly to questions of feasibility and to avoid questions of usefulness or desirability concerned with alternative techniques. This limitation was not entirely successful principally because of the following three items:

1. Information received from individuals involved in the present systems had notions of usefulness and desirability so intermingled with concepts of feasibility that they could not be separated.[5]

[5] Discussions with CDR W.J. Ecker 9G-MIS), CDR W.E. Whaley, Jr. (G-MIV), and LCDR J.R. Harrald (G-WEP-1), U.S. Coast Guard Headquarters, May/June 1976.

2. Extensive efforts aimed at evolving a new vessel casualty reporting system based on principles similar to SALT had apparently been successfully completed.[6] These studies extolled the usefulness and desirability of the new systems.

3. ORI analysts had extensive theoretical and practical experience with most of the associated safety analysis techniques and thus instinctively interjected their own estimates of usefulness and relative desirability.[7]

ORGANIZATION OF TECHNICAL MEMORANDUM

Section II of this memorandum contains a statement of the problem, Section III describes what is known about the problem, and Section IV proposes a general plan for resolving these difficulties.

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[6] Battelle, op. cit.

[7] Survey of Safety Analysis Techniques, ORI Technical Note 76-3, December 1972.

II. THE VESSEL CASUALTY PROBLEM

BACKGROUND

Many individuals and organizations have, in different ways, stated the shortcomings of the present vessel casualty reporting system. However, none of these statements contains an organized description of either the requirements of a better vessel casualty reporting system or the present shortcomings. Because of the limited scope of this study, no fully organized description will be attempted here. This section contains a summary of some of this criticism.

Individuals within the USCG have emphasized problems in describing accidents, recordkeeping, or data retrieval. The relative importance of a specific difficulty depends to a large extent on the critic's experience and current responsibility.

Several organizations have undertaken major studies[8] in order to improve the vessel casualty reporting system. These studies have proposed many major modifications to the present system. Additionally, they contain extensive criticism which touches nearly every aspect of the present system.

Although none of these studies have structured or organized the criticism, it appears that for purposes of discussion the present shortcomings could be organized into one of the following four categories:

1. Accident investigation
2. Accident reporting

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[8] Battelle, op. cit.

3. Data management and retrieval
4. Generation of measures of effectiveness.

One critic has presented the case that the present shortcomings all arise primarily from a single more fundamental difficulty in understanding or viewing the accident.[9]

Accident Investigation

Existing studies[10] document a great variety of difficulties with the present accident reporting system. These include problems with the current procedures for discovering an accident and the techniques of investigation. There is broad criticism of the essentially narrative and sequential nature of the investigation.

Individuals at USCG headquarters believe that the narrative format is required for reporting, but that a more structured investigative technique or format could be of assistance to the investigator. The specific proposal which has been made for the nature of this structure envisions a structure similar to a SALT diagram.

Accident Reporting

Existing studies criticize nearly all aspects of current accident reporting: the nature of the forms, the language and layout, the methods of completion and control, etc. There are broad criticisms of the narrative and sequential way the forms are completed.

There has been a general interest by USCG personnel in using Fault Tree or SALT techniques to restructure these forms. The paper by Benner suggests use of a new report format.

Data Management and Retrieval

Existing studies document a variety of difficulties with the current data management and retrieval systems. These include problems with coding, accuracy and precision of data, essential content, consistency of files, etc. A SALT tree classification technique for performing branching data searches has been developed and proposed for operational use.[11]

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[9] Benner, op. cit.

[10] Battelle, op. cit.

[11] Ibid.

USCG personnel have a continuing interest in improving casualty data management and retrieval. There are several on-going activities addressed to improving the accuracy and ease of these operations. There is a desire to at least cross-reference the vessel casualty file with the pollution incident file, and, if practical, in some sense, combine them.

Additionally, there is interest in using a SALT-type technique not only for classification, but also for simulation or replication of the accident.

Measures of Effectiveness

Current studies give little insight into what high level information can be obtained from any of the proposed systems. Their object seems to be only retrieval of more or better data. The problem of extracting information from the data is not addressed nor is the problem of measuring system effectiveness.

SUMMARY

Problems with the present vessel casualty and pollution incident reporting systems can be thought of as problems of:

1. Investigation
2. Reporting
3. Data management
4. Information retrieval.

A SALT-type safety analysis technique has been developed for data management.[12] There is continuing interest at U.S. Coast Guard headquarters for employing a SALT-type technique in accident investigation and reporting.

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[12] *Ibid.*

III. CURRENT UNDERSTANDING OF APPLICABLE TECHNIQUES

INTRODUCTION

This section summarizes the extent to which a SALT-based technique could assist the vessel casualty reporting system.

The techniques examined consist of Fault Tree, Safety Analysis Logic Tree (SALT), and Relative Accident Probabilty (RAP). These techniques are closely related.

Multilinear Event Sequencing (MES) is examined because it was believed that this technique complements the SALT technique.

FAULT TREE

Fault Tree is a functionally configured model that related undesirable conditions in a system operation to a particular undesired overall condition. Almost all Fault Tree literature describes the undesired overall condition as an undesired event. Event is not used in this discussion since event often implies position in time or sequence and Fault Tree specifically does not address time or sequence. This characteristic presents a major shortcoming for the use of fault trees in a vessel casualty reporting system. In the following sections the implications of this characteristic are examined.

A Fault Tree is constructed by starting with a single undesired overall condition based on a gross hazard analysis and then successively relating all probable causes to this condition. Combinations of "and" and "or" logic form the connections between conditions such that the paths through the tree (fault paths) define possible accident causes. A probability of the undesired condition may be calculated by combining the probability of occurrence

of the input conditions in accordance with the mathematical function of the logic gates relating these input conditions.

Since a single Fault Tree relates to a single undesired overall condition, and is in itself a static configuration, multiple undesired conditions and dynamic changes in configurations of causal events over various time frames are accounted for by interconnecting several fault trees. If important aspects of the investigation are sequential, the tree quickly becomes a configurational absurdity.

Summary

Fault Tree has the following characteristics of importance to the vessel casualty reporting system:

1. It is a functionally configured structure that starts at an undesired condition and branches to causal conditions.

2. It has no inherent sequential structure; sequences are added "after the fact" by replication of fault trees.

3. Since input data in the proper form is almost never generated and since correct mathematical computation in the absense of a rigorous time or sequence algorithm is so difficult, it is primarily a qualitative bookkeeping process and discipline for keeping track of configurational (and-or) aspects of causal conditions.

Thus, Fault Tree is the simplest and most straightforward method of describing the functional relations between accidents and causes. Other methods are required to describe the dynamic sequences of events over time.

SAFETY ANALYSIS LOGIC TREE (SALT)

SALT is configurationally and mathematically very similar to the fault tree. Unlike fault tree it contains both desired and undesired conditions. This is a major improvement if the system is to be used to sort or classify accidents. Because it forces yes or no decisions in classifying an accident, the accident is forced down through a SALT tree into a single causal location. Multiple causes cannot be easily accommodated. Thus, it is very useful for sorting in a gross sense[13] but has no simulative characteristics. As with the fault tree model, attempts to include sequential

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[13] M. Cornell, Recreational Boaters Requirements and Methods of Distress Notification Using Visual Signals, ORI Report to U.S. Coast Guard, published as Report CG-D-68-75, January 1975.

conditions lead to either factorial inclusions of sub-trees or loops; either quickly produces configurational absurdities.

RELATIVE ACCIDENT PROBABILITY (RAP)

RAP[14] has many attributes which might be expected of a sequential fault tree.

The tree itself is built to simulate the physical configuration of the system or device. It is thus a mimic of the physical accident paths. A rigorous syntax which defines the following is developed and applied to produce:

1. A complete sequence
2. All of the situations in the sequence
3. All of the activities in a situation
4. All of the mishaps in an activity
5. How a mishap stresses the accident path network.

Although each of these items has a specialized definition within the RAP format, the meaning is close enough to the common meaning that they need not be redefined here.

As a sequence progresses through each time frame, or from one situation to the next, the accident path network is updated, that is, recalculated. Thus, the accident path network keeps a running account of the safety situation over the complete sequence. Thus, RAP is highly simulative of both operations and the physical configuration, and is highly illustrative in showing differences in operations or hardware.

It is particularly easy to apply to those systems which are sequenced discretely through highly confined or even closed sequences; for example, special weapons. It is not presently suitable for handling a continuous or unconfined sequence such as might be defined in a vessel collision.

RAP generates an accident path network which monitors closely all conditions within a complicated system which is in danger of premature operation at any moment. A vessel collision can only occur at one point in the sequence, namely the last, and the conditions are entirely geometric. The accident path network (the simulation of the physical system) should thus be trivially short.

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[14] Rogers et al., Preliminary Analysis of the MK 48 Exploder (U), ORI Technical Report 407 (classified), and Cornell and Kirkland, TX-56 Nuclear Weapon Safety (U), ORI Technical Report 186 (classified).

Summary

RAP has the following characteristics of importance to vessel casualty reporting systems.

1. It is highly structured with respect to the physical configurations of the system (the accident paths).

2. It is highly structured with respect to the sequence the system is subjected to.

3. It is highly simulative.

4. Specific data is likely to exist or be amenable to observation.

5. It gives good visibility into the system and its operation.

Thus, RAP serves to highlight the fact that the difficulties of the vessel casualty reporting system problem are in the generation of the syntax of the sequences, and not in the accident paths. Additionally, since RAP models these aspects much more closely than Fault Tree or SALT, it provides a better overall accident process model.

MULTILINEAR EVENT SEQUENCING (MES)

Several of the difficulties which would be experienced in using RAP techniques for the vessel casualty reporting system problem have already been specifically addressed.[14] In addition, a simple syntax is offered which allows description of an accident in the following terms:

1. An accident involves a series of activities (perhaps parallel or converging, etc.).
2. An activity is a series of events.
3. An event is an important action by an actor.

An excellent method for closing the accident sequence at the beginning and end is offered. However, the sequence still seems unbounded in the possible sequences between the beginning and the end. Herein lies the major difficulty; it is the sequence itself which must be modeled. Not only does the complete network of possible sequences approach infinity, but since the principal variables are continuous, it is difficult to see how they might be denumerated.

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[14] Benner, op. cit.

Program Evaluation and Review Technique (PERT)[15] is also a multi-linear event sequencing technique. Several methods have been worked out to allow PERT-type modeling of sequences with alternative outcomes.[16] These techniques have been highly developed but, as they currently exist, do not provide suitable models for the accident sequence. They may, however, serve to further characterize the required sequence network.

CONCLUSIONS

It appears that any "SALT-type" technique developed for the vessel casualty or pollution incident reporting system will, in fact, correspond more closely to RAP than SALT. If a RAP-type technique is feasible, it will require a highly developed syntax and elements of the MES network. The syntax can be easily developed as required, but current network generation techniques seem inadequate and further research will be required.

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[15] McMillan and Gonzalez, Systems Analysis: A Computer Approach to Decision Models (Third Edition), Irwin, 1973 (or any standard text addressing PERT).

[16] H. Eisner, J. McDonnel, Decision Network Technology for System Development, ORI Technical Report 416, January 1967.

IV. POSSIBLE APPROACHES TO RAP/MES TYPE TECHNIQUES FOR THE VESSEL CASUALTY REPORTING SYSTEM

INTRODUCTION

For a RAP/MES type technique to be of use in the vessel casualty reporting system, the following three problems will have to be solved:

1. Development of an adequate measure of effectiveness.
2. Development of a clear and unambiguous syntax for the accident process.
3. Development of a method of displaying, a priori, the accident sequence network.

The following sections suggest approaches to solving these problems.

MEASURES OF EFFECTIVENESS

Because of the nature of a RAP/MES model, it seems likely that the overall measure of effectiveness should be quantitative and very likely be probabilistic. It should be probabilistic because of the manner in which the accident process is normally configured--i.e., no one event causes the accident but the accident becomes more likely at each event. At some event, the accident becomes a certainty. The data, if it were collected from all such situations, would reflect this probabilistic concept. Additionally, the measure should be quantitative so that its values can be measured at each step in the sequence. In this way, it can be determined where, and how much safety is lost at each point.

The following two such measures have appeal:

1. Probability of an accident (actually the probability that this sequence will result in an accident)

2. Point of closest approach (the expected point of closest approach which will result from this sequence).

While the probability of an accident at each stage of the sequence has great appeal, the input data may be very difficult to approximate or obtain. For this reason the expected point of closest approach seems a better choice. With cooperation of harbor pilots associations, data to support such a measure might be relatively easy to collect.

DEVELOPMENT OF A SYNTAX

The full question of how to separate causes and effects, define and display situations, events, mishaps, stresses, etc., is still unanswered. There is still too much ambiguity and confusion to actually reconstruct, even after an accident, an unambiguous network.

A good start at developing a syntax[17] has been made, and the definitions of the beginning and end of an accident are particularly appealing. It is likely that the proposed definitions and rules could be developed and made rigorous enough to handle an a priori model.

DEVELOPMENT OF A SEQUENTIAL NETWORK

The proposed Multilinear Event Sequence (MES) diagrams may be suitable for accident investigation but are clearly not suitable for a complete a priori analysis because of the previously-mentioned branching and combination problems. It is likely that the maxtix methods of Relative Accident Probability (RAP) could handle this difficulty and still give the required insight.

However, before either the MES or the RAP matrices could practically be developed, it seems likely that it would be necessary to classify and bound the sequences. If this is not done, the general network between the beginning and end will have too many a priori possibilities to conceptualize, much less enumerate.

If the syntax is properly worked out, it may help greatly in bounding the problem by defining either the space or time sequence so that it can be enumerated.

There are many possibilities of classifying to further restrict the possible networks and make them more tractable. For instance, the network might be classified by:

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[17] Benner, op. cit.

1. Geometry (meeting, crossing, overtaking)
2. Range at initial sighting
3. Time between initial sighting and collision
4. Size of vessel
5. Geographic area (port, channel segment)
6. Accident severity (in terms of lives lost or dollar cost).

None of these classifications seems to provide a special benefit for effectiveness measures. It is possible, however, that selective combinations might be useful.

APPENDIX H

SCENARIO MODEL, ENERGY EXCHANGE SUBMODEL:

DERIVATION OF E_D, ENERGY AVAILABLE FOR DEFORMING PLATE[1]

EQUATIONS OF MOTION

A ship of mass m_1 strikes a ship of mass m_2 at an angle α between the center lines of the ships as shown in Figure H.1, the ships having initial velocities, v_1, v_2, respectively. The collision occurs at a distance x from the center of the struck ship and exerts an instantaneous impulse at the point of contact. For purposes of this analysis, we assume that the geometric center of the ship is its center of mass.

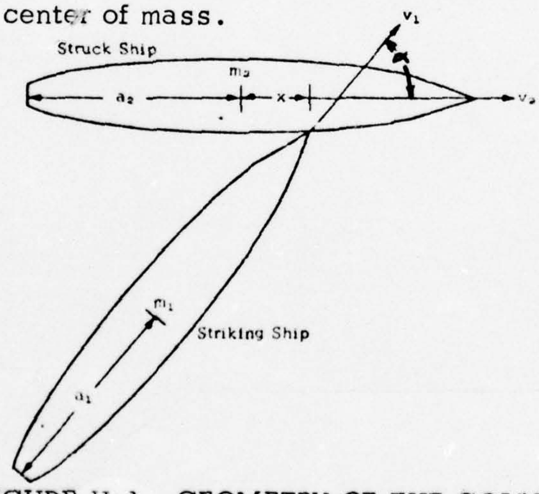

FIGURE H.1. GEOMETRY OF THE COLLISION

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[1] Flagwood, J. H., Ship Collisions at Varying Angles of Incidence, Naval Construction Establishment, Report No. NCRE/N 163, St. Leonard's Hill, Dunfermline, Fife, Scotland, February 1964.

The impulse at x is equivalent to an impulsive force I and an impulsive couple, N, i.e., the time integrals of the force and couple over the duration of the collision, at the centers of mass of each ship (Figure H.2).

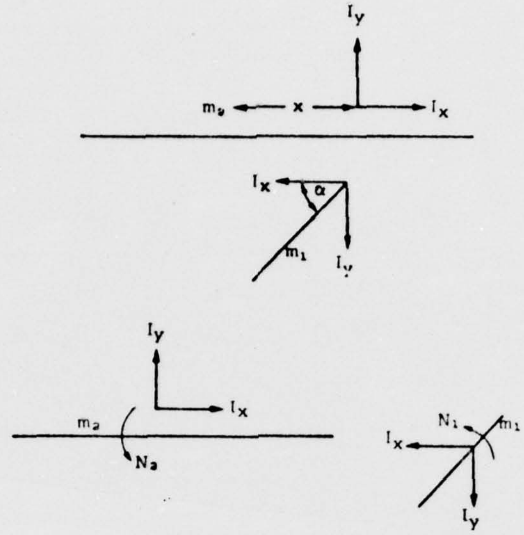


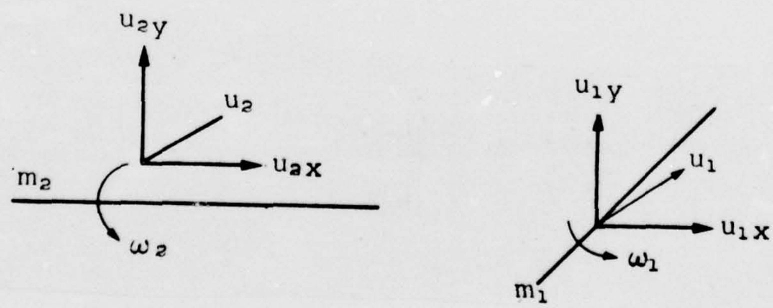
FIGURE H.2. MOTION AFTER COLLISION

It follows that

$$N_1 = a_1 I_x \sin \alpha - a_1 I_y \cos \alpha$$

$$N_2 = x I_y \qquad \text{(H.1)}$$

where I_x, I_y are components of the impulsive force I, and a_1 is the half length of the striking ship. Immediately after collision the ships have linear velocities, u_1, u_2, and rotational velocities, ω_1, ω_2, at the centers of mass as shown in Figure H.3.



Assumption: Center of Ship is Center of Mass

FIGURE H.3. MOTION AFTER COLLISION

The equations following from momentum considerations become

$$m_2' u_2 x - m_2 v_2 = I_x$$

$$m_2' u_{2y} = I_y$$

$$m_1 v_1 \cos \alpha - m_2' u_{1x} = I_x$$

$$m_1 v_1 \sin \alpha - m_1' u_{1y} = I_y$$

$$I_{01}' \omega_1 = N_1$$

$$I_{02}' \omega_2 = N_2 \qquad \text{(H.2)}$$

where u_{1x}, u_{1y}, u_{2x}, u_{2y} are the component velocities of u_1, u_2, and m_1', m_2', I_{01}', I_{02}' are the effective masses and rotational moments of inertia about the centers of mass.

The condition that contact is maintained at the point of collision gives

$$u_{2x} = u_{1x} - a_1 \omega_1 \sin \alpha$$

$$u_{2y} + x \omega_2 = u_{1y} + a_1 \omega_1 \cos \alpha \qquad \text{(H.3)}$$

and the effective masses and moments of inertia are defined by the equations

$$m_2'/m_1 = 1 + |\sin \theta_1|$$

$$m_2'/m_1 = 1 + |\sin \theta_2|$$

$$I_{01}' = \beta m_1 K_1^2 a_1^2$$

$$I_{02}' = \beta m_2 K_2^2 a_2^2 \qquad \text{(H.4)}$$

where

$$\sin \theta_1 = \frac{u_{1y} \cos \alpha - u_{1x} \sin \alpha}{u_1}$$

$$\sin \theta_2 = \frac{u_{2y}}{u_2}$$

and K_1, K_2 are the radii of gyration of the two ships about a vertical axis amid ships.

Equations (H.1) to (H.3) may be rewritten in the form:

$$u_{2x} = \frac{FD - CG}{FB - EC} \quad u_{2y} = \frac{BG - ED}{FB - EC}$$

$$u_{1x} = (v_1 \cos\alpha - \mu\epsilon_2 u_{2x} + \mu v_2)/\epsilon_1$$

$$u_{1y} = (v_1 \sin\alpha - \epsilon_2 u_{2y})/\epsilon_1 \qquad \text{(H.5)}$$

where

$\mu = m_2/m_1$

$B = \epsilon_1 + \mu\epsilon_2 + \mu\epsilon_1\epsilon_2 A_1 \sin^2\alpha.$

$C = E = -\mu\epsilon_1\epsilon_2 A_1 \sin\alpha\cos\alpha$

$D = v_1 \cos\alpha + \mu v_2(1 + \epsilon_1 A_1 \sin^2\alpha)$

$F = \epsilon_1 + \mu\epsilon_2 + \mu\epsilon_1\epsilon_2 A_1 \cos^2\alpha + \epsilon_1\epsilon_2 A_2$

$G = v_1 \sin\alpha - \mu\epsilon_1 v_2 A_1 \sin\alpha \cos\alpha$

$\epsilon_1 = m_1'/m_1$

$\epsilon_2 = m_2'/m_2$

$A_1 = \beta/K_1^2$

$A_2 = x^2/\beta K_2^2 a_2^2$.

When the effect of the mass of entrained water is neglected, i.e., when $\epsilon_1 = \epsilon_2$, the motion of the ships is completely determined by Equation (H.5). If the effective masses of the ships are defined by Equation (H.4) the motion of the ships is obtained by solving Equations (H.4) and (H.5) simultaneously.

ENERGY DISTRIBUTION

The energy absorbed in the collision and available to cause damage is given by

$$W = E_o - E_T - E_R \tag{H.6}$$

where E_o is the initial kinetic energy of the two ships before collision, E_T is the final translational kinetic energy and E_R is the final rotational energy of the ships. These energy terms are given by

$$E_o = \tfrac{1}{2}(m_1 v_1^2 + m_2 v_2^2)$$

$$E_T = \tfrac{1}{2}(m_1' u_1^2 + m_2' u_2^2)$$

$$E_R = \tfrac{1}{2}(I_{o1}' \omega_1^2 + I_{o2}' \omega_2^2)$$

and rewriting Equation (H.6) in a nondimensional form it follows that

$$\frac{W}{\frac{1}{2} m_1 v_1^2} = 1 + \mu\left(\frac{v_2}{v_1}\right)^2 - \epsilon_1\left(\frac{u_1}{v_1}\right)^2 - \mu\epsilon_2\left(\frac{u_2}{v_1}\right)^2 - \frac{1}{A_1}\left(\frac{a_1\,\omega_1}{v_1}\right)^2 - \frac{\mu}{A_2}\left(\frac{x\,\omega_2}{v_1}\right)^2. \tag{H.7}$$

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APPENDIX I

SCENARIO MODEL FORTRAN IV PROGRAM LISTING

```
          C*****************************************************************************
          C*                          PROGRAM  INPUT                                   *
          C*****************************************************************************
0001            IMPLICIT INTEGER (X)
0002            REAL*8 VARNAM(35)
0003            COMMON NM
0004            COMMON A(40),J,J1,J2,BASE(30),BASE1(10,4)
0005            MM=3
0006            DIMENSION B(10,25),X(23),Y(23),U(23),M(23)
          C     *********************  INITIALIZE ARRAYS TO ZEROES  *************
0007            DATA  B/250*0.0/,X/23*0/,Y/23*0.0/
0008            DATA U/23*0.0/,M/23*0/
0009            DO 75 L=1,30
0010            BASE(L)=0.
0011         75 CONTINUE
          C*****  35 VARIABLES ARE ASSIGNED VALUES IN THIS PROGRAM TO THE "A" VECTOR
          C       THE FIRST 3 - S, ITURN, IENG - DEAL WITH THE BASICS OF ANY RUN.
          C           -S IS THE SCENARIO BEING STUDIED AND ITS VALUES ARE:
          C                 1 - PARALLEL MEETING
          C                 2 - PARALLEL OVERTAKING
          C                 3 - LONG RANGE CROSSING
          C                 4 - SUDDEN APPEARANCE
          C                 5 - HEAD-ON
          C
          C           -ITURN INDICATES THE TURN RESPONSE MADE:
          C                 1 - NO TURN
          C                 2 - LEFT TURN
          C                 3 - RIGHT TURN
0012            CONTINUE
          C           -IENG INDICATES THE TYPE OF ENGINE ORDER MADE:
          C                 1 - NO ORDER
          C                 2 - APPROPRIATE USE OF DECELERATION
          C                 3 - APPROPRIATE USE OF ACCELERATION
          C                 4 - APPROPRIATE USE OF DECELERATION OR ACCELERATION
          C                 5 - BLIND DECELERATION
          C                 6 - BLIND ACCELERATION
          C           READ IN SCENARIO AND TYPE OF RESPONSE FOR THE RUN
0013            READ(5,21)S,ITURN,IENG
0014         21 FORMAT(F10.0,2I10)
          C
0015            IS=S
0016
0017
0018            GO TO (101,102,103,104,105),IS
0019        101 WRITE(6,111)
0020        111 FORMAT(15X,'PARALLEL MEETING SCENARIO'//)
0021            GO TO 24
0022        102 WRITE(6,112)
0023        112 FORMAT(15X,'PARALLEL OVERTAKING SCENARIO'//)
0024            GO TO 24
0025        103 WRITE(6,113)
0026        113 FORMAT(15X,'LONG RANGE CROSSING SCENARIO'//)
0027            GO TO 24
0028        104 WRITE(6,114)
0029        114 FORMAT(15X,'SUDDEN APPEARANCE SCENARIO'//)
0030            GO TO 24
```

```
0031          105 WRITE(6,115)
0032          115 FORMAT(15X,'HEAD ON MEETING SCENARIO'//)
0033           24 CONTINUE
            C
            C
            C         THE NEXT 8 VARIABLES DESCRIBE SOME BASIC CHARACTERISTICS OF
            C         THE TWO SHIPS BEING MODELED, THERE ARE FOUR PAIRS OF VARIABLES:
            C        -FIRST, THE CRABBING ANGLE IN A TURN FOR EACH SHIP - IN DEGREES.
            C        -SECOND, THE PIVOT POINT IN A TURN FOR EACH SHIP - AS A FRACTION
            C              OF SHIP LENGTH FROM THE BOW,
            C        -THIRD, THE TRANSFER TO STEADY-TURN RADIUS RATIO, A/R
            C        -FOURTH, THE WIDTH OF EACH SHIP - AS A FRACTION OF LENGTH
            C
            C
            C
            C             READ IN THE CONSTANT SYSTEM PARAMETER VALUES
0034             READ(5,25)CRAB1,CRAB2,PIVOT1,PIVOT2,TURN1,TURN2,WIDTH1,WIDTH2
0035           25  FORMAT(8F5.0)
            C******  THE NEXT 23 DATA CARDS HAVE THE VALUES OF THE 23 SYSTEM PARAMETERS
            C         WHICH MAY BE SET UP FOR SENSITIVITY STUDY, EACH CARD CONTAINS A
            C         TRIPLET OF VALUES WHICH ESTABLISH THE NUMBER OF VALUES OF EACH
            C         PARAMETER TO BE USED, THE LOWEST VALUE, AND THE DIFFERENCE BETWEEN
            C         EACH VALUE, FOR EXAMPLE, THE LAST CARD CONTAINS THE VELOCITY FOR
            C         SHIP 1, IF THE TRIPLET READS 5,6,2 THEN 5 VELOCITIES ARE TO BE USED
            C         AT 2 KNOT INTERVALS BEGINNING AT 6 - I.E. 6,8,10,12,14 KNOTS,
            C         THE FIRST NUMBER OF THE TRIPLET IS STORED IN THE X VECTOR, THE SECOND
            C******  IN THE U VECTOR AND THE THIRD IN THE Y VECTOR.
            C             READ IN SYSTEM PARAMETER VALUES WHICH ARE, OR COULD BE,
            C             SET UP FOR SENSITIVITY ANALYSIS
0036             READ(5,20)(X(I),U(I),Y(I),I=1,23)
0037           20 FORMAT(I10,2F10.0)
            C
            C         THE STRAIN ENERGY TO RUPTURE IS READ IN AS 10E8 FT-LBS,
            C         THESE FOUR STATEMENTS CONVERT A "2" TO THE ACTUAL VALUE
            C         FOR PROGRAM USE, I.E. "2.0E8",
0038              U(5)=U(5)*1.E8
0039              U(6)=U(6)*1.E8
0040             Y(5)=Y(5)*1.E8
0041             Y(6)=Y(6)*1.E8
0042             IF(S.GT.2.) GO TO 29
            C
            C
            C         THE LAST SET OF DATA IS THE BASELINE CASE INFORMATION
            C         WHICH IS USED IN THE OUTPUT SUBROUTINE TO CALCULATE
            C         PERCENTAGE CHANGES IN PROBABILITY OF COLLISION AND RUPTURE
            C         AS WELL AS AVERAGE AND MAXIMUM COLLISION ENERGY.
            C         THESE 9 DATA CARDS ARE UNNECESSARY FOR LONG RANGE
            C         CROSSING, SUDDEN APPEARANCE, AND HEAD-ON SCENARIOS,
            C
            C             READ IN BASELINE CASE DATA VALUES
0043             READ (5,28)((BASE1(I,J),J=1,4),I=1,9)
0044           28 FORMAT(4F15.0)
0045           29 CONTINUE
            C
            C******  THE B MATRIX, TWO DIMENSIONAL, CONTAINS A LIST OF ALL THE VALUES
            C         OF EACH PARAMETER WHICH COULD HAVE MORE THAN 1 VALUE,
```

```
0046             DO 400 I=1,23
0047             LOOP=X(I)
0048             DO 400 J=1,LOOP
0049             B(J,I)=U(I)
0050             U(I)=U(I)+Y(I)
0051         400 CONTINUE
           C
           C
           C******  COMPUTE: J1=THE TOTAL NO OF INPUT COMBINATIONS FOR THIS RUN
           C******  COMPUTE: J2=THE NUMBER OF PARAMETERS HAVING MORE THAN 1 VALUE
           C
0052             J2=0
0053             J1=1
0054             N2=4
0055             DO 500 I=1,23
0056             J1=J1*X(I)
0057             IF (X(I) .EQ. 1) GO TO 500
0058             BASE(N2)=I
0059             N2=N2+1
0060             J2=J2+1
0061         500 CONTINUE
           C
           C*****  STORE S, IENG, & ITURN, AS WELL AS THE 4 PAIRS OF SHIP PARAMETERS
           C         DISCUSSED EARLIER,  INTO THE "A" VECTOR
           C         THE "A" VECTOR HAS ALL THE VALUES OF EVERY SYSTEM PARAMETER
           C
           C*****  VARIABLES WHICH CANNOT BE VARIED IN A RUN
0062             A(24)=CRAB1
0063             A(25)=CRAB2
0064             A(26)=PIVOT1
0065             A(27)=PIVOT2
0066             A(28)=TURN1
0067             A(29)=TURN2
0068             A(30)=WIDTH1
0069             A(31)=WIDTH2
0070             A(32)=C
0071             A(33)=R
0072             A(34)=IENG
0073             A(35)=S
           C******  VARIABLES WHICH CAN BE VARIED
           C                A(1)= DISPLACEMENT TONNAGE, SHIP 2 - LONG TONS
           C                A(2)= DISPLACEMENT TONNAGE, SHIP 1 - LONG TONS
           C                A(3)= LENGTH, SHIP 2 - FT.
           C                A(4)= LENGTH, SHIP 1 - FT.
           C                A(5)= HULL RUPTURE ENERGY, SHIP 2 - FT-LBS.
           C                A(6)= HULL RUPTURE ENERGY, SHIP 1 - FT-LBS.
           C                A(8)= TIME LAG FROM ALPHA 1 TO RESPONSE ORDER, SHIP 1
           C                A(7)= TIME LAG FROM ALPHA1 TO RESPONSE ORDER, SHIP 2
           C                A(9)= LENGTH OF SPIRAL TURN TAIL (B),SHIP2 - FT.
           C                A(10)=LENGTH OF SPIRAL TURN TAIL (B),SHIP1 - FT.
           C                A(11)=FINAL TURN RADIUS, SHIP 2 - FT.
           C                A(12)=FINAL TURN RADIUS, SHIP 1 - FT.
           C                A(13)=ACCELERATION, SHIP 2 - FT/SEC.SQUARED
           C                A(14)=ACCELERATION, SHIP 1 - FT/SEC.SQUARED
           C                A(15)=DECELERATION, SHIP 2 - FT/SEC.SQUARED
           C                A(16)=DECELERATION, SHIP 1 - FT/SEC.SQUARED
```

```
                C                 A(17)=ALPHA2, ENGINE ORDER TIME LAG, SHIP 2 - SEC,
                C                 A(18)=ALPHA2, ENGINE ORDER TIME LAG, SHIP 1 - SEC,
                C                 A(19)=ALPHA RESPONSE, SHIP 2 - FRACTION OF TRACK SEPARATION
                C                 A(20)=ALPHA RESPONSE, SHIP 1 - FRACTION OF TRACK SEPARATION
                C                 A(21)=CHANNEL TRACK SEPARATION
                C                 A(22)=INITIAL VELOCITY, SHIP 2 - KNOTS
                C                 A(23)=INITIAL VELOCITY, SHIP 1 - KNOTS
                C***********
                C        PRINT OUT THE INITIAL VALUE OF EACH OF THE 35 SYSTEM PARAMETERS
0074                  WRITE(6,204)
0075              204 FORMAT(5X,'HERE IS A LIST OF THE INITIAL VALUE OF EACH SYSTEM ',
                     C'PARAMETER:'/)
0076                  DO 205 III=1,35
0077              205 WRITE(6,206)III,VARNAM(III),A(III)
0078              206 FORMAT(1X,I5,5X,A8,' = ',F14,3)
                C
0079                  GO TO (67,68,69), ITURN
0080               67 TURN=0.
0081                  GO TO 70
0082               68 TURN=1.
0083                  GO TO 70
0084               69 TURN=-1.
0085               70 CONTINUE
0086                  J=1
                C
                C******  THE NEXT ROUTINE ORGANIZES EACH SET OF INPUT VARIABLES AND PUTS
                C        IT INTO THE "A" VECTOR (ACCESSED SYSTEMATICALLY FROM THE "B" MATRIX)
                C        AND THEN WE LEAVE THIS PROGRAM (PROGRAM 'INPUT') TO GO TO SUBROUTINE
                C        "COLBOX". AFTER LINKING WITH SUBSEQUENT SUBROUTINES CONTROL
                C        RETURNS TO THIS PROGRAM AND THE NEXT SET OF INPUT VALUES ARE
                C        PUT INTO "A". A TOTAL OF J1 COMBINATIONS OF INPUT SETS ARE
                C        USED. OUTPUT IS PRINTED FOR EACH SET. FOR INSTANCE, WITH 5
                C        TRACK SEPARATIONS AND 4 DECELERATION VALUES THERE WOULD BE
                C        A TOTAL OF 20 SETS OF OUTPUT INFORMATION - ALL COMBINATIONS OF
                C        TRACK SEPARATION AND DECELERATIONS,. THE INPUT PROGRAM IS DESIGNED
                C        TO PRODUCE ALL THE REQUIRED DATA NECESSARY FOR AN ANALYSIS OF
                C******  VARIANCE OR REGRESSION STUDY.
                C
                C
                C
0087                  LOOP1=X(1)
0088                  LOOP2=X(2)
0089                  LOOP3=X(3)
0090                  LOOP4=X(4)
0091                  LOOP5=X(5)
0092                  LOOP6=X(6)
0093                  LOOP7=X(7)
0094                  LOOP8=X(8)
0095                  LOOP9=X(9)
0096                  LOOP10=X(10)
0097                  LOOP11=X(11)
0098                  LOOP12=X(12)
0099                  LOOP13=X(13)
0100                  LOOP14=X(14)
0101                  LOOP15=X(15)
0102                  LOOP16=X(16)
```

```
0103          LOOP17=X(17)
0104          LOOP18=X(18)
0105          LOOP19=X(19)
0106          LOOP20=X(20)
0107          LOOP21=X(21)
0108          LOOP22=X(22)
0109          LOOP23=X(23)
        C        EXECUTE 23 NESTED LOOPS FOR THE FIRST 23 VARIABLES IN "A" MATRIX
0110          DO 600 X1=1,LOOP1
0111          DO 600 X2=1,LOOP2
0112          DO 600 X3=1,LOOP3
0113          DO 600 X4=1,LOOP4
0114          DO 600 X5=1,LOOP5
0115          DO 600 X6=1,LOOP6
0116          DO 600 X7=1,LOOP7
0117          DO 600 X8=1,LOOP8
0118          DO 600 X9=1,LOOP9
0119          DO 600 X10=1,LOOP10
0120          DO 600 X11=1,LOOP11
0121          DO 600 X12=1,LOOP12
0122          DO 600 X13=1,LOOP13
0123          DO 600 X14=1,LOOP14
0124          DO 600 X15=1,LOOP15
0125          DO 600 X16=1,LOOP16
0126          DO 600 X17=1,LOOP17
0127          DO 600 X18=1,LOOP18
0128          DO 600 X19=1,LOOP19
0129          DO 600 X20=1,LOOP20
0130          DO 600 X21=1,LOOP21
0131          DO 600 X22=1,LOOP22
0132          DO 600 X23=1,LOOP23
        C
        C        THE "M" MATRIX CONTAINS THE COLUMNS OF "B" FOR EACH VARIABLE IN
        C        WHICH THE DESIRED PARAMETERS ARE STORED FOR THIS PASS
0133          M(1)=X1
0134          M(2)=X2
0135          M(3)=X3
0136          M(4)=X4
0137          M(5)=X5
0138          M(6)=X6
0139          M(7)=X7
0140          M(8)=X8
0141          M(9)=X9
0142          M(10)=X10
0143          M(11)=X11
0144          M(12)=X12
0145          M(13)=X13
0146          M(14)=X14
0147          M(15)=X15
0148          M(16)=X16
0149          M(17)=X17
0150          M(18)=X18
0151          M(19)=X19
0152          M(20)=X20
0153          M(21)=X21
0154          M(22)=X22
```

```
0155            M(23)=X23
          C
          C
          C              ASSIGN PARAMETER VALUES TO THE "A" MATRIX (A(1) TO A(23))
0156            DO 505 I=1,23
0157            A(I)=B(M(I),I)
0158        505 CONTINUE
          C**********    J IS A COUNTER WHICH IS INCREMENTED AND PRINTED OUT EACH TIME
          C**********    A NEW SET OF INPUT VALUES IS EVALUATED
          C
0159            WRITE (6,100) J
0160        100 FORMAT('1','ROUND',I3,/)
          C**********    THIS LITTLE ROUTINE FIGURES OUT WHICH OF THE 23 VARIABLES
          C              IS BEING RUN FOR SENSITIVITY (I.E. HAS CHANGING VALUES), AND
          C**********    PRINTS VALUE ON EACH TRANSIT THROUGH THE SUBPROGRAMS.
          C
0161            DATA VARNAM(1)/8HTONS 2  /,VARNAM(2)/8HTONS 1  /
0162            DATA VARNAM(3)/8HLENGTH 2/,VARNAM(4)/8HLENGTH 1/
0163            DATA VARNAM(5)/8HENERGY 2/,VARNAM(6)/8HENERGY 1/
0164            DATA VARNAM(7)/8HTM LAG 2/,VARNAM(8)/8HTM LAG 1/
0165            DATA VARNAM(9)/8HSPRL=B 2/,VARNAM(10)/8HSPRL=B 1/
0166            DATA VARNAM(11)/8HSPRL=R 2/,VARNAM(12)/8HSPRL=R 1/
0167            DATA VARNAM(13)/8HACCEL 2 /,VARNAM(14)/8HACCEL 1 /
0168            DATA VARNAM(15)/8HDECEL 2 /,VARNAM(16)/8HDECEL 1 /
0169            DATA VARNAM(17)/8HALPHA2 2/,VARNAM(18)/8HALPHA2 1/
0170            DATA VARNAM(19)/8HALPHA1 2/,VARNAM(20)/8HALPHA1 1/
0171            DATA VARNAM(21)/8HTRAK SEP/
0172            DATA VARNAM(22)/8HVEL 2   /,VARNAM(23)/8HVEL 1   /
0173            DATA VARNAM(24)/8HCRAB 1  /,VARNAM(25)/8HCRAB 2  /
0174            DATA VARNAM(26)/8HPIVOT 1 /,VARNAM(27)/8HPIVOT 2 /
0175            DATA VARNAM(28)/8HTRANSF 1/,VARNAM(29)/8HTRANSF 2/
0176            DATA VARNAM(30)/8HBEAM/L 1/,VARNAM(31)/8HBEAM/L 2/
0177            DATA VARNAM(32)/8H--------/,VARNAM(33)/8HTURN RES/
0178            DATA VARNAM(34)/8HENG ORDR/,VARNAM(35)/8HSCENARIO/
0179            IF (J2 .EQ. 0)  GO TO  450
0180            JJ2=J2+3
0181            DO 300 N2=4,JJ2
0182            I=BASE(N2)
0183            WRITE (6,200) VARNAM(I),A(I)
0184        200 FORMAT (1X,A8, ' = ',F14.3)
0185        300 CONTINUE
0186        450 JA35=A(35)
0187            GO TO (510,510,520,520,540), JA35
0188        510 IF (S .EQ. 2.0) GO TO 511
0189            SCENAR=1.
0190            GO TO 512
0191        511 SCENAR=-1.
          C
          C        THIS NEXT SECTION UTILIZES THE ENGINE ORDER VARIABLE, IENG, TO
          C     TO SET UP THE ACCELERATION AND DECELERATION USED IN CALCULATIONS
          C     IN SUBROUTINE "COLBOX".  THAT SUBROUTINE CALCULATES THE SIZE OF THE
          C     COLLISION REGION BY FINDING THE FRONT, MIDDLE, AND BACK BOUNDARIES.
          C     VARIABLE "D5" IS ACCELERATION FOR THE FRONT BOUNDARY CALCULATION
          C     AND "D6" IS FOR THE MIDDLE AND BACK BOUNDARIES.  EXAMPLE:
          C           APPROPRIATE DECELERATION = NO DECELERATION IS USED FOR THE
          C     FRONT BOUNDARY CALCULATION, I.E. D5 = 0.0.  THE INPUTTED DECELERATION
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      C                   VALUE IS USED, HOWEVER, FOR THE MIDDLE AND BACK BOUNDARIES.
        512 GO TO (1,2,3,4,5,6), IENG
          1 D5=0.
            D6=0.
            GO TO 514
          2 D5=0.
            D6=-A(15)
            GO TO 514
          3 D5=-A(13)
            D6=0.
            GO TO 514
          4 D5=-A(13)
            D6=-A(15)
            GO TO 514
          5 D5=-A(15)
            D6=D5
            GO TO 514
          6 D5=-A(13)
            D6=D5
        514 N=1
      C          "COLBOX IS CALLED TWICE.  FIRST, FOR VESSEL 1 MAKING THE TURN
      C          ERROR,  SECOND, FOR VESSEL 2 MAKING THE TURN ERROR.  ALL APPROPRIATE
      C            SYSTEM PARAMETERS VALUES ARE PASSED TO THE SUBROUTINES IN THE
      C          ARGUMENT LIST OF THE CALL STATEMENTS.
            CALL COLBOX(A(21),A(19),A(12),A(11),A(28)*A(12),A(29)*A(11),
           CA(10),A(9),A(4),A(3),A(30)*A(4),A(31)*A(3),A(23),A(22),D5,
           CD6,A(26),A(27),A(24),A(25),A(17),A(7),N,TURN,SCENAR)
            IF (N .EQ. 0) GO TO 600
            GO TO (11,22,33,44,55,66 ) , IENG
         11 D5=0.
            D6=0.
            GO TO 515
         22 D5=0.
            D6=-A(16)
            GO TO 515
         33 D5=-A(14)
            D6=0.
            GO TO 515
         44 D5=-A(14)
            D6=-A(16)
            GO TO 515
         55 D5=-A(16)
            D6=D5
            GO TO 515
         66 D5=-A(14)
            D6=D5
        515 N=2
            CALL COLBOX(A(21),A(20),A(11),A(12),A(29)*A(11),A(28)*A(12),A(9),
           CA(10),A(3),A(4),A(31)*A(3),A(30)*A(4),A(22),A(23),D5,D6,
           CA(27),A(26),A(25),A(24),A(18),A(8),N,TURN,SCENAR)
            GO TO 600
        520 DEC= -A(15)
            CALL LRC(A(11),A(29)*A(11),A(9),A(23),A(22), DEC ,A(17),A(4),
           CA(3),A(30)*A(4),A(31)*A(3),A(27),A(25))
            J=J+1
            GO TO 600
```

```
0238        530 DLG=A(17)/3.
0239            DEC=-A(15)
0240            CALL HALT(A(22), DEC ,DLG,TIME,0.0,DIST)
0241            WRITE (6,535) TIME,DIST
0242        535 FORMAT(1X,//,1X,'STOPPING TIME = ',F7.1,//,1X,'STOPPING ',
               C'DISTANCE = ',F7.1)
0243            J=J+1
0244            GO TO 600
0245        540 CALL HEADON(A(11),A(29)*A(11),A(9),A(23),A(22),A(4),A(3),
               CA(30)*A(4)/2+50.,A(31)*A(3),A(17),A(27),A(25))
          C******  RETURN FROM SUBROUTINE PROGRAM OUTPUT IS TO THE STATEMENT
          C******  "600 CONTINUE" AFTER ALL CALCULATIONS FOR THE INPUT SET IS COMPLETE,
0246        600 CONTINUE
0247            STOP
0248            END
```

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      C***********************************************************************
      C*                         PROGRAM COLBOX                               *
      C***********************************************************************
      C          AN EXPLANATION OF THE WORKINGS OF THIS SUBROUTINE AND IT'S
      C        SATELLITE SURROUTINES IS NEAR THE END OF SECTION II
      C        OF THE MANEUVERING ANALYSIS REPORT.
      C
0001        SUBROUTINE COLBOX(S,A,R1,R2,A1,A2,B1,B2,XL1,XL2,W1,W2,VV1,VV2,
           CD5,D6,F1,F2,CC1,CC2,TT,T5,N,C,X)
0002        COMMON MM
0003        COMMON  AMTRX(40),INDXJ,INDXJ1,INDXJ2,BASE(30),BASE1(10,4)
0004        COMMON BB1,FF1,AA1,BB2,FF2,AA2
0005        COMMON DD(10,4),EE(10,4),FF(10,4),GG(10,4)
0006        V1=VV1*1.689
0007        V2=VV2*1.689
0008        T2=TT/3.
0009        C1=CC1/57.3
0010        C2=CC2/57.3
0011        C2=ABS(C*C2)
0012        D1=0.
0013        D2=D6
0014        REAL L1,L2
0015        L1=XL1
0016        L2=XL2
0017        T6=1.E9
0018        E2=90./57.3
0019        E6=90./57.3
0020        G6=R2
0021        U6=V2
0022        Z6=0.
0023        IF (D6 .GT. 0.) GO TO 4
0024        GO TO 6
0025      4 IF (C .EQ.0) GO TO 5
0026        CALL STOP(A2,B2,R2,V2,D2,T2,G6,E6,Z6,U6,T6)
0027        GO TO 6
0028      5 CALL HALT(V2,D2,T2,T6,U6,Y6)
0029      6 T=50.
0030        Y8=1.E9
0031        T3=0
0032        T1=0
0033        DO 155 I=1,6
0034    150 CALL SPIRAL (A1,B1,R1,V1,D1,T1,T,Q1,Q3,Z1,Z3,E1,E3,U1,A7)
0035        IF (ABS(T-1000.) .GT. 1000.) GO TO  5290
0036        X1=-G1*COS(Z1)-A*S+A1+F1*XL1*COS(E1)
0037        X2=Z3*(-G3*COS(Z1)+G1*SIN(Z1)-F1*XL1*SIN(E1)*E3)
0038        T=T-(X1/X2)
0039        IF (ABS(X1) .LT. 1) GO TO 200
0040    155 CONTINUE
0041        GO TO 5290
0042    200 IF (T .LT. 0) GO TO 5290
      C*****                              FRONT OF COLLISION BOX
0043        D2=D5
0044        T3=T
0045        T3=T3+T5
0046        T=T3+50.
0047        DO 480 I1=1,6
```


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          CALL SPIRAL (A1,B1,R1,V1,D1,T1,T,Q1,Q3,Z1,Z3,E1,E3,U1,A7)
          IF (ABS(T-1000.) .GT. 1000.) GO TO  5290
      250 IF (C .EQ. 0) GO TO 300
          TIME=T-T3
          CALL SPIRAL (A2,B2,R2,V2,D2,T2,TIME,Q2,Q4,Z2,Z4,E2,E4,U2,A7)
          IF (TIME .LT. 0.) GO TO 5290
      270 P2=Q2-.5*D*W2
      300 P1=Q1-.5*X*W1
          XM1=F1*XL1
          XM2=(1-F2)*XL2
          X1=A1-S
          X1=X1-P1*COS(Z1)
          X1=X1+XM1*COS(E1-C1)
          IF (C .EQ. 0) GO TO 350
          X2=-A2+P2*COS(Z2)
          X2=X2+XM2*COS(E2-C2)
      350 X3=(-Q3*COS(Z1)+P1*SIN(Z1))*Z3
          X3=X3-XM1*SIN(E1-C1)*E3*Z3
          IF (C .EQ. 0) GO TO 400
          X4=(-P2*SIN(Z2)+Q4*COS(Z2))*Z4
          X4=X4-XM2*SIN(E2-C2)*E4*Z4
          X2=D*X2
          X4=C*X4
          GO TO 450
      400 X2=-.5*W2
          X4=0
      450 T=T-(X1-X2)/(X3-X4)
          IF (ABS(X1-X2) .LT. 1) GO TO 500
      480 CONTINUE
          GO TO 5290
      500 IF (T .LT. T3) GO TO 5290
             Y=-B1-P1*SIN(Z1)
          Y=Y-XM1*SIN(E1-C1)
          Y=X*Y
          IF (C .EQ. 0) GO TO 510
          Y=Y+XM2*SIN(E2-C2)
          Y=Y-P2*SIN(Z2)-B2+F2*L2
          GO TO 650
      510 IF ((T-T3) .LT. T6) GO TO  550
          Y=Y+Y6+L2
          U2=U6
          GO TO 650
      550 TIME=T-T3
          CALL DECEL (V2,D2,TIME,T2,Y,U2)
          Y=Y+L2
      650 T7=T
          Y7=Y
C*****                     MIDDLE OF COLLISION BOX
          D2=D6
          DO 920 I2=1,6
          CALL SPIRAL (A1,B1,R1,V1,D1,T1,T,Q1,Q3,Z1,Z3,E1,E3,U1,A7)
          IF (ABS(T-1000.) .GT. 1000.) GO TO  5290
      700 IF (C .EQ. 0) GO TO 750
          Q2=Q6
          Z2=Z6
          E2=E6
```

```
      U2=U6
      Z4=0
      E4=0
      G4=0
      IF ((T-T3) .GT. T6) GO TO   730
      TIME=T-T3
      CALL SPIRAL (A2,B2,R2,V2,D2,T2,TIME,G2,G4,Z2,Z4,E2,E4,U2,A7)
      IF (TIME .LT. 0.) GO TO 5290
  730 P2=G2
  750 P1=G1
      XM1=P1*XL1
      XM2=-P2*XL2
      X1=A1-S
      X1=X1-P1*COS(Z1)
      X1=X1+XM1*COS(E1-C1)
      IF (C .EQ. 0) GO TO 800
      X2=-A2+P2*COS(Z2)
      X2=X2+XM2*COS(E2-C2)
  800 X3=(-G3*COS(Z1)+P1*SIN(Z1))*Z3
      X3=X3-XM1*SIN(E1-C1)*E3*Z3
      IF (C .EQ. 0) GO TO 850
      X4=(-P2*SIN(Z2)+G4*COS(Z2))*Z4
      X4=X4-XM2*SIN(E2-C2)*E4*Z4
      X2=C*X2
      X4=C*X4
      GO TO 900
  850 X2=0
      X4=0
  900 T=T-(X1-X2)/(X3-X4)
      IF (ABS(X1-X2) .LT. 1) GO TO  950
  920 CONTINUE
      GO TO 5290
  950 IF (T .LT. T3) GO TO 5290
          Y=-B1-P1*SIN(Z1)
      Y=Y-XM1*SIN(E1-C1)
      Y=X*Y
      IF (C .EQ. 0) GO TO 970
      Y=Y+XM2*SIN(E2-C2)
      Y=Y-P2*SIN(Z2)-B2+F2*L2
      GO TO 1100
  970 IF ((T-T3) .LT. T6) GO TO 1050
      Y=Y+Y6
      U2=U6
      GO TO 1100
 1050 TIME=T-T3
      CALL DECEL (V2,D2,TIME,T2,Y,U2)
 1100 UU1=U1
      UU2=U2
      EE1=X*E1
      EE2=(1.+C)*90./57.3-C*E2
      Y8=Y
C*****                      REAR OF COLLISION BOX
      D2=D6
      DO 1360  I3=1,10
      CALL SPIRAL (A1,B1,R1,V1,D1,T1,T,Q1,Q3,Z1,Z3,E1,E3,U1,A7)
      IF (ABS(T-1000.) .GT. 1000.) GO TO  5290
```

```
      IF (C .EQ. 0.) GO TO 1200
      Z2=Z6
      E2=E6
      G2=G6
      U2=U6
      Z4=0
      G4=0
      E4=0
      IF ((T-T3) .GT. T6) GO TO    1170
      TIME=T-T3
      CALL SPIRAL (A2,B2,R2,V2,D2,T2,TIME,Q2,G4,Z2,Z4,E2,E4,U2,A7)
      IF (TIME .LT. 0.) GO TO 5290
 1170 P2=G2+.5*W2
 1200 P1=G1+.5*X*W1
      XM1=-(1-F1)*XL1
      XM2=-F2*XL2
      X1=A1-S
      X1=X1-P1*COS(Z1)
      X1=X1+XM1*COS(E1-C1)
      IF (C .EQ. 0) GO TO 1250
      X2=-A2+P2*COS(Z2)
      X2=X2+XM2*COS(E2-C2)
 1250 X3=(-G3*COS(Z1)+P1*SIN(Z1))*Z3
      X3=X3-XM1*SIN(E1-C1)*E3*Z3
      IF (C .EQ. 0) GO TO 1300
      X4=(-P2*SIN(Z2)+G4*COS(Z2))*Z4
      X4=X4-XM2*SIN(E2-C2)+E4*Z4
      X2=D*X2
      X4=D*X4
      GO TO 1350
 1300 X2=.5*W2
      X4=0
 1350 T=T-(X1-X2)/(X3-X4)
      IF (ABS(X1-X2) .LT. 1) GO TO 1400
 1380 CONTINUE
      GO TO 5290
 1400 IF (T .LT. T3) GO TO 5290
      Y=-B1-P1*SIN(Z1)
      Y=Y-XM1*SIN(E1-C1)
      Y=X*Y
      IF (C .EQ. 0) GO TO 1410
      Y=Y+XM2*SIN(E2-C2)
      Y=Y-P2*SIN(Z2)-B2+F2*L2
      GO TO 1550
 1410 IF ((T-T3) .LT. T6) GO TO 1450
      Y=Y+Y6
      U2=U6
      GO TO 1550
 1450 TIME=T-T3
      CALL DECEL (V2,D2,TIME,T2,Y,U2)
 1550 Y9=Y
      B5=Y7-Y9
      F5=Y7-Y8
      A5=Y8-Y9
      IF (F5 .LT. 0.) GO TO 5290
      IF (A5 .LT. 0.) GO TO 5290
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      GO TO (2100,2200), N
 2100 BB1=B5
      FF1=F5
      AA1=A5
      DO 2250 JJ=1,MM
      DD(JJ,1)=UU1/1.689
      EE(JJ,1)=UU1/1.689
      FF(JJ,1)=UU2/1.689
      GG(JJ,1)=UU2/1.689
      DD(JJ,2)=UU2/1.689
      EE(JJ,2)=UU2/1.689
      FF(JJ,2)=UU1/1.689
      GG(JJ,2)=UU1/1.689
      DD(JJ,3)=.5*XL2
      EE(JJ,3)=.5*XL1
      FF(JJ,3)=.5*XL2
      GG(JJ,3)=.5*XL1
      DD(JJ,4)=(EE1+EE2)*57.3
      EE(JJ,4)=(EE1+FE2)*57.3
      FF(JJ,4)=(EE1+EE2)*57.3
      GG(JJ,4)=(EE1+EE2)*57.3
 2250 CONTINUE
      GO TO 2300
 2200 BB2=B5
      FF2=F5
      AA2=A5
 2300 K=1
      C1=X*C1
      C2=D*C2
      XM=MM
      T=T7
      DO 5100 J1=1,MM
      AK=J1
      Y=Y7+(AK-.5)*(Y8-Y7)/XM
      GO TO 2500
 2400 DO 5000 J2=1,MM
      AJ=J2
      Y=Y8+(AJ-.5)*(Y9-Y8)/XM
 2500 DO 4000 I4=1,20
      B1=ABS(B1)
      A2=ABS(A2)
      CALL SPIRAL (A1,B1,R1,V1,D1,T1,T,G1,G3,Z1,Z3,E1,E3,U1,A7)
      IF (ABS(T-1000.) .GT. 1000.) GO TO  5200
      B1=X*B1
      E1=X*E1
      G3=X*G3
      Z1=X*Z1
      Z3=X*Z3
      Z2=Z6
      E2=E6
      G2=G6
      U2=U6
      Z4=0.
      G4=0.
      E4=0.
      IF ((T-T3) .GE. T6) GO TO 3000
```


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```
2800 IF (C .EQ. 0.) GO TO 3000
     TIME=T-T3
     CALL SPIRAL(A2,B2,R2,V2,D2,T2,TIME,G2,G4,Z2,Z4,E2,E4,U2,A7)
     IF (TIME .LT. 0.) GO TO 5200
3000 A2=C*A2
     E2=(1.-C)*90./57.3+C*E2
     Z2=(1.-C)*90./57.3+C*Z2
     G4=C*G4
     Z4=Z4*C
     GO TO (3100,3500), K
3100 X1=A1-S-G1*COS(Z1)
     X1=X1+F1*XL1*COS(E1-C1)
     X3=(G1*SIN(Z1)-G3*COS(Z1))*Z3
     X3=X3-F1*XL1*SIN(E1-C1)*E3*Z3
     IF (C .EQ. 0.) GO TO 3200
     G2=G2-.5*D*W2
     X2=-A2+G2*COS(Z2)
     X4=(G4*COS(Z2)-G2*SIN(Z2))*Z4
     GO TO 3250
3200 X2=-.5*W2
     X4=0.
3250 Y1=-B1-G1*SIN(Z1)
     Y1=Y1-F1*XL1*SIN(E1-C1)
     Y3=-(G1*COS(Z1)+G3*SIN(Z1))*Z3
     Y3=Y3-F1*XL1*COS(E1-C1)*E3*Z3
     IF (C .EQ. 0.) GO TO 3300
     Y2=Y-F2*XL2+B2+G2*SIN(Z2)
     Y4=(G2*COS(Z2)+G4*SIN(Z2))*Z4
     GO TO 3400
3300 IF ((T-T3) .LT. T6) GO TO 3350
     Y2=Y-Y6
     U2=0.
     Y4=0.
     GO TO 3400
3350 TIME=T-T3
     YY=-Y
     CALL DECEL (V2,D2,TIME,T2,YY,U2)
     Y2=-YY
     Y4=U2
3400 G0=(Y2-Y1)*COS(E2-C2)+(X2-X1)*SIN(E2-C2)
     G1=(Y4-Y3)*COS(E2-C2)+(X4-X3)*SIN(E2-C2)
     G1=G1-((Y2-Y1)*SIN(E2-C2)-(X2-X1)*COS(E2-C2))*E4*Z4
     T=T-G0/G1
     IF (ABS(G0) .LT. .1) GO TO 4500
     GO TO 4000
3500 G1=G1+.5*X*W1
     X1=A1-S-G1*COS(Z1)
     X3=(G1*SIN(Z1)-G3*COS(Z1))*Z3
     Y1=-B1-G1*SIN(Z1)
     Y3=-(G1*COS(Z1)+G3*SIN(Z1))*Z3
     IF (C .EQ. 0.) GO TO 3600
     X2=-A2+G2*COS(Z2)
     X2=X2-F2*XL2*COS(E2-C2)
     X4=(G4*COS(Z2)-G2*SIN(Z2))*Z4
     X4=X4+F2*XL2*SIN(E2-C2)*E4*Z4
     Y2=Y+B2-F2*XL2*G2*SIN(Z2)
```

```
      Y2=Y2+F2*XL2*SIN(E2-C2)
      Y4=(G4*SIN(Z2)+G2*COS(Z2))*Z4
      Y4=Y4+F2*XL2*COS(E2-C2)*E4*Z4
      GO TO 3800
 3600 IF ((T-T3) .LT. T6) GO TO 3700
      Y2=Y-Y6
      Y4=0.
      U2=0.
      X2=0.
      X4=0.
      GO TO 3800
 3700 TIME=T-T3
      X2=0.
      X4=0.
      YY=-Y
      CALL DECEL (V2,D2,TIME,T2,YY,U2)
      Y2=-YY
      Y4=U2
 3800 G0=(Y2-Y1)*COS(E1-C1)+(X2-X1)*SIN(E1-C1)
      G1=-((Y2-Y1)*SIN(E1-C1)-(X2-X1)*COS(E1-C1))*E3*Z3
      G1=G1+(Y4-Y3)*COS(E1-C1)+(X4-X3)*SIN(E1-C1)
      T=T-G0/G1
      IF (ABS(G0) .LT. .1) GO TO 4100
 4000 CONTINUE
      GO TO 5200
 4100 XL=(Y2-Y1)/SIN(E1-C1)+F1*XL1
      E2=(180./57.3)-E2
      IF (XL .GE.0.)  GO TO 4150
      XL=0.
      U1=UU1
      U2=UU2
 4150 XL=.5*XL1-XL
      IF (N .EQ. 2) GO TO 4200
      EE(J2,1)=U1/1.689
      EE(J2,2)=U2/1.689
      EE(J2,3)=XL
      EE(J2,4)=(E1+E2)*57.3
      GO TO  5000
 4200 GG(J2,2)=U1/1.689
      GG(J2,1)=U2/1.689
      GG(J2,3)=XL
      GG(J2,4)=(E1+E2)*57.3
      GO TO  5000
 4500 XL=(Y2-Y1)/SIN(E2-C2)+F2*XL2*ABS(D)
      E2=(180./57.3)-E2
      IF (XL .GE.0.)  GO TO 4550
      XL=0.
      U1=UL1
      U2=UL2
 4550 XL=.5*XL2-XL
      IF (N .EQ. 2) GO TO  4800
      DD(J1,1)=U1/1.689
      DD(J1,2)=U2/1.689
      DD(J1,3)=XL
      DD(J1,4)=(E1+E2)*57.3
      GO TO  5100
```


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```
 4900 FR(J1,2)=U1/1,689
      FR(J1,1)=U2/1,689
      FR(J1,3)=XL
      FR(J1,4)=(E1+E2)*57,3
      GO TO  5100
 5000 CONTINUE
      IF (N ,EQ, 1) GO TO  5050
      CALL ENEREX
 5050 GO TO 5500
 5100 CONTINUE
 5200 IF (K ,EQ, 2) GO TO 5500
      K=2
      GO TO 2400
 5290 WRITE (6,8000)
      N=0
 5500 RETURN
 8000 FORMAT (1X,
     C'PARAMETERS OUT OF RANGE FOR THIS PROGRAM - NO SOLUTION')
      END
```


399

```
C*******************SUBROUTINE LONG RANGE CROSSING*******************
C           THIS SUBROUTINE COMPUTES MINIMUM RANGE, BEARING, DISTANCE
C           TO CPA AND TIME TO CPA FOR TEN CROSSING ANGLES BETWEEN
C           160 DEG (NEARLY HEAD-ON) AND 70 DEG (NEARLY OVERTAKING) FOR
C           THE FOLLOWING MANEUVERS:
C                1 - LEFT TURN RESPONSE
C                2 - RIGHT TURN RESPONSE
C                3 - DECELERATION RESPONSE
C                4 - RIGHT TURN WITHOUT CROSSING PATH RESPONSE
      SUBROUTINE LRC (R,A,B,VV1,VV2,D,TTT,XL1,XL2,W1,W2,F,CC)
      REAL L1,L2
      L1=XL1
      L2=XL2
      C=CC/57.3
      V1=VV1*1.689
      V2=VV2*1.689
      TT=TTT/3.
      T2=TT
      DO 1000 J=1,4
      GO TO (100,200,500,850), J
  100 WRITE(6,110)
  110 FORMAT(/1X,'LEFT TURN RESPONSE')
      O=1.
      GO TO 300
  200 WRITE (6,210)
  210 FORMAT(/1X,'RIGHT TURN RESPONSE')
      O=-1.
  300 CALL STOP (A,B,R,V2,D,TT,Q6,E6,Z6,U6,T6)
      WRITE (6,310)
  310 FORMAT( 5X,'ANGLE',10X,'DISTANCE',10X,'TCPA',10X,
     C'BEARING',10X,'RANGE')
      T=50.
      DO 400 I=1,10
      G9=80-I*10
      G=G9/57.3
      DO 380 N=1,10
      Q=Q6
      E=E6
      Z=Z6
      Q4=0.
      E4=0.
      Z4=0.
      U=U6
      IF (T .GT. T6) GO TO 350
      CALL SPIRAL (A,B,R,V2,D,TT,T,Q,Q4,Z,Z4,E,E4,U,A7)
  350 P=Q+C*.5*W2
      X=A-P*COS(Z)
      X4=(P*SIN(Z)-Q4*COS(Z))*Z4
      X=X+F*XL2*COS(E-C)
      X4=X4-F*XL2*SIN(E-C)*E4*Z4
      X=O*X
      X4=O*X4
      X=X-.5*W1*SIN(G)+(V1*T-XL1)*COS(G)
      X4=X4+V1*COS(G)
      Y=B-F*XL2+P*SIN(Z)
      Y4=(Q4*SIN(Z)+P*COS(Z))*Z4
```

```
      Y=Y+F*XL2*SIN(E-C)
      Y4=Y4+F*XL2*COS(E-C)*E4*Z4
      Y=Y+.5*W1*COS(G)+(V1*T-XL1)*SIN(G)
      Y4=Y4+V1*SIN(G)
      H1=.5*(W2+W1*SIN(G))
      H0=(V2+V1*SIN(G))/(V1*COS(G))
      Y0=Y
      Y=Y+H0*H1+XL2+.5*W1*COS(G)
      T=T-(Y-H0*X)/(Y4-H0*X4)
      IF (ABS(Y-H0*X) .LT. .01) GO TO 385
  380 CONTINUE
      GO TO 400
  385 IF (C .EQ. -1.) GOTO 388
      IF ((E-C) .LT. G)  GO TO 400
  388 Y=Y0
      T0=(X-H1)/(V1*COS(G))
      B0=ATAN(X/Y)*57.3
      Y0=Y-X*TAN(G)
      R0=SQRT(X**2+Y**2)
      G0=90+G9
      WRITE (6,390) G0,Y0,T0,B0,R0
  390 FORMAT (5X, 5(F10.3,5X))
  400 CONTINUE
      GO TO 1000
  500 WRITE (6,510)
  510 FORMAT(/1X,'DECELERATION RESPONSE')
      WRITE(6,310)
      T=100.
      G9=80.
      DO 800 II=1,10
      G9=G9-10.
      G=G9/57.3
      DO 600 NN=1,10
      IF (T .GT. TT) GO TO 550
      D=0.
  550 A7=-D*(1-EXP(-(T-T2)/T2))
      U2=V2-D*(T-T2)-T2*A7
      Y=-.5*D*(T-T2)**2-T2*U2+V2*T+T2*V2
      Y=Y+.5*W1*COS(G)
      Y=Y+(V1*T-L1)*SIN(G)
      T0=-(W2+W1*SIN(G))/(V1*COS(G))
      T0=T0+T-L1/V1
      Y=Y-T0*(V2+V1*SIN(G))+L2+.5*W1*COS(G)
      T=T-Y/(U2-V2)
      IF (ABS(Y) .LT. .01) GO TO  700
  600 CONTINUE
      GO TO  800
  700 T0=-(W2+W1*SIN(G))/(V1*COS(G))+T-L1/V1
      X=-.5*(W2+W1*SIN(G))+(V1*T-L1)*COS(G)
      Y=T0*(V2+V1*SIN(G))-L2-.5*W1*COS(G)
      Y0=Y-X*TAN(G)
      B0=ATAN(X/Y)*57.3
      G0=90+G9
      R0=SQRT(X**2+Y**2)
      WRITE (6,390) G0,Y0,T0,B0,R0
  800 CONTINUE
```

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```
              GO TO 1000
          850 WRITE (6,860)
          860 FORMAT(1X,//,1X,'RIGHT TURN NOT CROSSING PATH',//,5X,'ANGLE',
             C10X,'DISTANCE',10X,'TCPA',10X,'BEARING',10X,'RANGE')
              G9=170.
              DO 990 I2=1,10
              G9=G9-10.
              G=G9/57.3
              Y2=B+A*ATAN(.5*G)
              Y1=(Y2+L2)*V1/V2
              RANGE=SQRT(Y1**2+Y2**2-2*Y1*Y2*COS(G))
              SB=Y1*SIN(G)/RANGE
              TB=SB/SQRT(1-SB**2)
              BEAR=ATAN(TB)
              BEAR=BEAR*57.3
              TCPA=Y2/V2
              WRITE (6,390)G9,Y2,TCPA,BEAR,RANGE
          990 CONTINUE
         1000 CONTINUE
              RETURN
              END
```


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      C********************SUBROUTINE HEAD-ON**************************
      C          THIS SUBROUTINE COMPUTES THE MINIMUM RANGE AND TIME TO
      C          CPA AT WHICH A TURNING MANEUVER IN A HEAD-ON SCENARIO WILL
      C          NEED TO BE INITIATED TO AVOID COLLISION.
      C
            SUBROUTINE HEADON(R,A,B,VV1,VV2,XL1,XL2,W1,W2,TTT,F,CC)
            V1=VV1*1.689
            V2=VV2*1.689
            TT=TTT/3.
            C=CC/57.3
            T=50.
            DO 100 J=1,10
            CALL SPIRAL(A,B,R,V2,0.,TT,T,G,G4,Z,Z4,E,E4,U,A7)
            P=G+.5*W2
            X=A-P*COS(Z)+F*XL2*COS(E-C)-.5*W1
            X4=(P*SIN(Z)-G4*COS(Z))*Z4
            X4=X4-F*XL2*SIN(E-C)*E4*Z4
            T=T-X/X4
            IF(ABS(X) .LT. .01) GO TO 200
        100 CONTINUE
            GO TO 500
        200 Y=-F*XL2+B+P*SIN(Z)+F*XL2*SIN(E-C)+V1*T
            TCPA=Y/(V1+V2)
            WRITE(6,300) Y,TCPA
        300 FORMAT(/9X,'HEADON RESPONSE DISTANCE',F10.1/20X,'TCPA ',F10.1)
        500 RETURN
            END
```

```
C***************SATELLITE SUBROUTINE SPIRAL************************
C          THIS SUBROUTINE COMPUTES THE POSITION, HEADING, VELOCITY,
C          DECELERATION, AND THEIR DERIVATIVES FOR A VESSEL AT ANY
C          GIVEN TIME IN A SPIRAL TURN.
C
      SUBROUTINE SPIRAL(A,B,R,V,D,T0,T,Q,DQ,Z,W,E,DE,U,A7)
      XK=SQRT(A**2+B**2)/R
      C=XK-1
      IF (XK .EQ. 1)  GO TO 50
      H=(XK*B)/(C*A)
      GO TO 100
   50 H=1
  100 W=V/(R*SQRT((1+C)**2+(H*C)**2))
      E=SQRT(H**2+1)
      IF (T .GT. T0) GO TO 150
      D=0.
  150 Z=W*T-ATAN(B/A)
      FNA=1.
      FNM=SQRT((E*C*FNA)**2+2*C*FNA+1)
      FNN=ALOG((FNM+1)/(C*FNA)+1)
      FNO=(1/E)*ALOG(FNM+C*E*FNA+1/E)
      FNG=-(R/H)*(FNM-FNN+FNO)
      FNG1=FNG
      FNA=EXP(-H*(Z+ATAN(B/A)))
      FNM=SQRT((E*C*FNA)**2+2*C*FNA+1)
      FNN=ALOG((FNM+1)/(C*FNA)+1)
      FNO=(1/E)*ALOG(FNM+C*E*FNA+1/E)
      FNG=-(R/H)*(FNM-FNN+FNO)
      FNP=FNG-FNG1
      FNR=-(E**2*C*FNA+1)*C*FNA*H/FNM
      A7=W**2*R*FNR
      U=W*R*FNM-D*(T-T0)
      SO=FNP-.5*D*(T-T0)**2
      IF (D .EQ. 0) GO TO 250
       A7=    A7    -D*(1-EXP(-(T-T0)/T0))
      U=U+D*T0*(1-EXP(-(T-T0)/T0))
      SO=SO+D*T0*(T-T0+T0*(EXP(-(T-T0)/T0)-1))
      DO 200 N=1,6
      Z=Z-((FNP-SO)/(R*FNM))
      IF (ABS(FNP-SO) .LT. 1) GO TO 250
      FNA=EXP(-H*(Z+ATAN(B/A)))
      FNM=SQRT((E*C*FNA)**2+2*C*FNA+1)
      FNN=ALOG((FNM+1)/(C*FNA)+1)
      FNO=(1/E)*ALOG(FNM+C*E*FNA+1/E)
      FNG=-(R/H)*(FNM-FNN+FNO)
      FNP=FNG-FNG1
  200 CONTINUE
  220 T=-1.E9
      GO TO 5290
  250 FNA=EXP(-H*(Z+ATAN(B/A)))
      FNB=R*(1+C*FNA)
      FNC=-R*C*H*FNA
      FND=R*H**2*FNA*C
      FNE=FNC*SIN(Z)+FNB*COS(Z)
      FNF=FND*SIN(Z)+FNC*COS(Z)*2-FNB*SIN(Z)
      FNG=-FNC*COS(Z)+FNB*SIN(Z)
```


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      FNH=-FND*COS(Z)+2*FNC*SIN(Z)+FNB*COS(Z)
      FNI=FNE/FNG
      FNJ=(FNF*FNG-FNE*FNH)/(FNG**2)
      FNK=ATAN(FNI)
      FNL=FNJ/(FNI**2+1)
      W=U/(R*FNM)
      G=FNB
      DG=FNC
      E=FNK
      DE=FNL
 5290 RETURN
      END
```

305

```
C******************SATELLITE SUBROUTINE STOP***********************
C          THIS SUBROUTINE COMPUTES THE MINIMUM TIME REQUIRED BY A
C          VESSEL TO STOP ALONG A SPIRAL TURN, AS WELL AS ITS FINAL
C          POSITION AND HEADING
      SUBROUTINE STOP (A,B,R,V,D,TO,G,E,Z,U,T)
      T=TO+100
      DO 50 I=1,10
      CALL SPIRAL(A,B,R,V,D,TO,T,G,DG,Z,DZ,E,DE,U,A7)
      IF  (T,GT, 10000) GO TO   80
      IF  (T ,LT, 0,)  GO TO  80
      T=T-U/A7
      IF (ABS(U) ,LT, ,01) GO TO 100
   50 CONTINUE
   80 T=1,E7
  100 RETURN
      END
```


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```
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             C*****************SATELLITE SUBROUTINE DECEL**********************
             C          THIS SUBROUTINE COMPUTES THE POSITION, VELOCITY, AND THEIR
             C          DERIVATIVES FOR A VESSEL AT ANY GIVEN TIME WHEN DECELERATING
             C          CLONG A STRAIGHT COURSE
 0001              SUBROUTINE DECEL(V,D,T,TO,Y,U)
 0002              IF (T .GT.TO) GO TO 50
 0003              D=0
 0004           50 Y=Y-V*T+.5*(T-TO)**2*D
 0005              Y=Y-D*TO*(T-TO+TO*(EXP(-(T-TO)/TO)-1))
 0006              U=V+D*TO*(1-EXP(-(T-TO)/TO))-D*(T-TO)
 0007              RETURN
 0008              END
```


(307)

```
C*******************SATELLITE SUBROUTINE HALT***********************
C          THIS SUBROUTINE COMPUTES THE MINIMUM TIME REQUIRED BY A
C          VESSEL TO STOP ALONG A STRAIGHT COURSE.
      SUBROUTINE HALT(V,D,T0,T,U,Y)
      T=T0+100
      DO 50 I=1,10
      IF  (T.GT. 10000) GO TO   20
      IF (T .LT. 0.)  GO TO  20
      A7=-D*(1-EXP(-(T-T0)/T0))
      U=-D*(T-T0)+D*T0*(1-EXP(-(T-T0)/T0))+V
      T=T-U/A7
      IF (ABS(U) .LT. .01) GO TO 100
   50 CONTINUE
   20 T=1.E7
  100 Y=-.5*D*(T-T0)**2+D*T0*(T-T0+T0*(EXP(-(T-T0)/T0)-1))+V*T
      Y=-Y
  200 RETURN
      END
```

```
              C*******************************************************************************
              C*                          PROGRAM ENEREX                                      *
              C*******************************************************************************
0001                SUBROUTINE ENEREX
0002                COMMON MM
0003                COMMON A(40),J,J1,J2,BASE(30),BASE1(10,4)
0004                COMMON BB1,FF1,AA1,BB2,FF2,AA2
0005                COMMON D(10,4),E(10,4),F(10,4),G(10,4)
0006                COMMON R(10),S(10),P(10),Q(10)
              C
              C**********     INITIALIZE R,S,P,Q MATRICES TO ZERO
              C
0007                DO 25 I=1,MM
0008                R(I)=0.
0009                S(I)=0.
0010                P(I)=0.
0011                Q(I)=0.
0012             25 CONTINUE
              C**********     THE FOLLOWING ROUTINE BRANCHES TO 1 OF 4 SETS
              C               OF STATEMENTS WHICH ESTABLISH APPROPRIATE INPUT VALUES FOR
              C               THE ENERGY EXCHANGE CALCULATIONS.
              C                           CASE 1 - SHIP 1 TURNS AND HITS SHIP 2
              C                           CASE 2 - SHIP 1 TURNS AND IS HIT BY 2
              C                           CASE 3 - SHIP 2 TURNS AND HITS SHIP 1
              C                           CASE 4 - SHIP 2 TURNS AND IS HIT BY 1
0013                CONTINUE
              C               TURNING IN THIS CONTEXT MEANS CAUSING A COLLISION THREAT.
              C               EACH CASE IS THE FRONT OR BACK REGION OF A COLLISION BOX IN
              C               WHICH THE DEFENDING SHIP IS ASSUMED TO BE (WITH UNIFORM
              C               PROBABILITY OF BEING AT ANY POINT IN THE REGION) CASE 1,
              C               FOR EXAMPLE IS THE FRONT REGION OF SHIP 2'S BOX WHERE IF
              C               THE BOW OF SHIP 2 WAS ANYWHERE IN THAT FRONT HE WOULD BE HIT.
              C               IF HE WERE AT THE REAR OF THE FRONT REGION HE WOULD BE STRUCK
              C               NEAR THE BOW, WHEREAS HAD HE BEEN FURTHER ADVANCED AND AT THE
              C               HEAD OF THE FRONT THE COLLISION WOULD OCCUR ON HIS STERN.
              C               WE PICK  N  POINTS EVENLY SPACED IN THE FRONT PART OF THE
              C               COLLISION BOX, CALCULATE THE GEOMETRY OF THE ENSUING COLLISION
              C               AS WELL AS FINAL VELOCITIES (ALL DONE IN SUBROUTINE "COLBOX")
              C               AND CALCULATE, IN THIS PROGRAM, THE COLLISION ENERGY ASSOCIATED
              C               WITH EACH POINT.
              C                         A SIMILAR PROCESS IS DONE
              C               FOR THE BACK PORTION OF THE COLLISION BOX WHERE SHIP 2 IS THE
              C               HITTER, ALSO FOR THE COLLISION BOX OF SHIP 1 WHERE SHIP 2
              C               COMMITTED THE ERROR OF TURNING.  THUS 40 POINTS IN ALL ARE
              C               EVALUATED FOR THE RESULTING ENERGY WHICH IS ABSORBED BY THE
              C******         HULL PLATE AND STRUCTURE OF THE TWO SHIPS.
0014                CONTINUE
              C           DEFINITION OF VARIABLES
              C                V1 - VELOCITY OF STRIKING SHIP (FT/SEC)
              C                V2 - VELOCITY OF STRUCK SHIP (FT/SEC)
              C                Z - POSITION OF HIT FROM CENTER OF STRUCK SHIP (+ DIRECTION
              C                                IS TOWARD BOW)
              C                A1 - HALF LENGTH OF STRIKING SHIP
              C                A2 - HALF LENGTH OF STRUCK SHIP
              C                D1 - GROSS TONS OF STRIKING SHIP
              C                D2 - GROSS TONS OF STRUCK SHIP
```


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```
      C*********************     CASE 1
      C
  100 DO 150 I0=1,MM
      I=I0
      V1=D(I,1)*1,689
      V2=D(I,2)*1,689
      Z=D(I,3)
      X=D(I,4)/57,3
      A1=,5*A(4)
      A2=,5*A(3)
      D1=A(2)
      D2=A(1)
      ICTR=1
      GO TO 455
  150 R(I)=W
      CONTINUE
      C*********************     CASE 2
      C
  200 DO 250 I1=1,MM
      I=I1
      V1=E(I,2)*1,689
      V2=E(I,1)*1,689
      Z=E(I,3)
      X=E(I,4)/57,3
      A1=,5*A(3)
      A2=,5*A(4)
      D1=A(1)
      D2=A(2)
      ICTR=2
      GO TO 455
  250 S(I)=W
      CONTINUE
      C*********************     CASE 3
      C
  300 DO 350 I2=1,MM
      I=I2
      V1=F(I,2)*1,689
      V2=F(I,1)*1,689
      Z=F(I,3)
      X=F(I,4)/57,3
      A1=,5*A(3)
      A2=,5*A(4)
      D1=A(1)
      D2=A(2)
      ICTR=3
      GO TO 455
  350 P(I)=W
      CONTINUE
      C*********************     CASE 4
      C
  400 DO 450 I3=1,MM
      I=I3
      V1=G(I,1)*1,689
      V2=G(I,2)*1,689
      Z=G(I,3)
      X=G(I,4)/57,3
```


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```
            A1=.5*A(4)
            A2=.5*A(3)
            D1=A(2)
            D2=A(1)
            ICTR=4
            GO TO 455
      450   Q(I)=W
            CONTINUE
            GO TO 1000
      455   V5=(V2**2+V1**2)-(2*V1*V2*COS(X))
            ZERO=0.
            V4=AMAX1(V5,ZERO)
            V3=SQRT(V4)
            IF (V3 .GT. 0.) GO TO 500
            C=700.
            GO TO 550
      500   C=(V2-V1*COS(X))/V3
      550   SS=V2/V1
C                CONVERT TO POUNDS AND THEN TO SLUGS (THE ENGLISH UNIT OF MASS)
            D1=D1*2240
            D2=D2*2240
            R1=D1/32.2
            R2=D2/32.2
            S1=R1
            S2=R2
            DATA E1/1./,E2/1./
            U=R2/R1
            A4=1.8
            A5=1.8*Z**2/A2**2
            X1=2*X
C                PERFORM ITERATIVE PROCEDURE TO ESTABLISH CORRECT "EFFECTIVE MASS
C                OF SHIPS", S1 AND S2. EFFECTIVE MASS INCLUDES THE MASS OF
C              ENTRAINED WATER SURROUNDING THE SHIPS.
      600   B=E1+U*E2+U*E1*E2*A4*((1-COS(X1))/2)
            C=-U*E1*E2*A4*SIN(X)*COS(X)
            EE=-U*E1*E2*A4*SIN(X)*COS(X)
            DD=V1*COS(X)+U*V2*(1+E1*A4*((1-COS(X1))/2))
            FF=E1+U*E2+U*E1*E2*A4*((1+COS(X1))/2) +E1*E2*A5
            GG=V1*SIN(X)-U*E1*V2*A4*SIN(X)*COS(X)
            U8=((FF*DD)-(C*GG))/((FF*B)-(EE*C))
            U9=((B*GG)-(EE*DD))/((FF*B)-(EE*C))
            U7=(V1*COS(X)-U*E2*U8+U*V2)/E1
            U6=(V1*SIN(X)-U*E2*U9)/E1
            U1=SQRT(U7**2+U6**2)
            U2=SQRT(U8**2+U9**2)
            P1=(U6*COS(X)-U7*SIN(X))/U1
            P2=(U9/U2)
            S1=(1+ABS(P1))*R1
            Z1=S1/R1
            S2=(1+ABS(P2))*R2
            Z2=S2/R2
            Y=ABS(Z1-E1)
            IF (Y .LE. .01) GO TO 650
            E1=Z1
            E2=Z2
            GO TO 600
```

```
 650 Y2=ABS(Z2-E2)
     IF (Y2 .LE. .01) GO TO 700
     E1=Z1
     E2=Z2
     GO TO 600
 700 W1=(U7-U8)/(A1*SIN(X))
     W2=(U6+A1*W1*COS(X)-U9)/Z
     XI1=.55*R1*A1**2
     XI2=.55*R2*A2**2
C
C*********    E7 - TOTAL ENERGY DISSIPATED IN COLLISION
C             E8 - ENERGY USED IN CHANGING DIRECTION OF LINEAR MOTION
C             E9 - ENERGY USED IN CAUSING SHIPS TO SPIN
C             W - ENERGY LEFT OVER AFTER CONSERVATION OF MOMENTUM
C                 CONDITIONS ARE SATISFIED.  W IS THE COLLISION
C                 ENERGY WHICH WILL IN SOME WAY BE ABSORBED BY THE
C                 HULL PLATE AND STRUCTURE OF THE COLLIDING SHIPS, IN FT-LBS.
C             N3 - FRACTION OF STRIKING SHIP'S LINEAR KINETIC ENERGY
C*********        BEFORE COLLISION USED FOR HULL DEFORMATION.
C
     E7=.5*(R1*V1**2+R2*V2**2)
     E8=.5*(S1*U1**2+S2*U2**2)
     E9=.5*(XI1*W1**2+XI2*W2**2)
     W=E7-E8-E9
     N3=W/(.5*R1*V1**2)
C
C         BRANCH BACK TO BEGINNING OF SUBROUTINE AND STORE THE
C         COLLISION ENERGY, W, IN ONE OF THE FOUR 1X10 VECTORS, R,S,P,OR Q,
C         FOR USE IN THE NEXT SUBROUTINE - "OUTPUT"
C
     GO TO (150,250,350,450), ICTR
1000 CALL OUTPUT
     RETURN
     END
```

AD-A043 054 OPERATIONS RESEARCH INC SILVER SPRING MD RESOURCE AN--ETC F/G 13/2
SPILL RISK ANALYSIS PROGRAM. METHODOLOGY DEVELOPMENT AND DEMONS--ETC(U)
APR 77 L L STOEHR, C H MORGAN, F J REIFFLER DOT-CG-31571-A
UNCLASSIFIED ORI-TR-964-VOL-1 USCG-D-21-77 NL

4 OF 4
AD A043 054

END
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```
C*                    PROGRAM OUTPUT                                   *
C***********************************************************************
C*                         SUBROUTINE OUTPUT                           *
C***********************************************************************
C
C
C*********     IT IS THE JOB OF THIS PROGRAM TO USE THE INFORMATION
C              ABOUT THE SIZE OF THE 2 COLLISION BOXES (ONE FOR SHIP 1
C              MAKING AN ERROR IN TURNING AND ONE FOR THE SIMILAR ERROR
C              COMMITTED BY SHIP 2),THE SIZE OF THE FRONT AND BACK OF
C              EACH BOX, AND THE COLLISION ENERGY FOR THE 4N POINTS,
C
      SUBROUTINE OUTPUT
      COMMON MM
      COMMON A(40),J,J1,J2,BASE(30),BASE1(10,4)
      COMMON B1,F1,A1,B2,F2,A2
      COMMON D(10,4),E(10,4),H(10,4),G(10,4)
      COMMON R(10),S(10),P(10),Q(10)
      DIMENSION T(10),C(10,10),F(4),U(10,10)
      REAL*8 ERR(10),HIT(10)
      DATA ERR(1)/8HEITHER  /,ERR(2)/8HEITHER  /,ERR(3)/8HEITHER  /
      DATA ERR(4)/8H   1    /,ERR(5)/8H   2    /,ERR(6)/8H   1    /
      DATA ERR(7)/8H   1    /,ERR(8)/8H   2    /,ERR(9)/8H   2    /
      DATA HIT(1)/8HEITHER  /,HIT(2)/8H   1    /,HIT(3)/8H   2    /
      DATA HIT(4)/8HEITHER  /,HIT(5)/8HEITHER  /,HIT(6)/8H   2    /
      DATA HIT(7)/8H   1    /,HIT(8)/8H   1    /,HIT(9)/8H   2    /
      XM=MM
C                      DEFINITION OF VARIABLES
C*********     B1 = LENGTH OF COLLISION BOX (FT), SHIP 1 ERRED
C              B2 = LENGTH OF COLLISION BOX (FT), SHIP 2 ERRED
C              F1 = FRONT OF COLLISION BOX B1
C              A1 = BACK OF COLLISION BOX B1
C              B1=F1+A1
C              SAME FOR B2,F2,A2
C              F(I) = FRACTION OF COLLISION BOX=F(1)+F(2)=1, F(3)+F(4)=1
C
C
C
  400 F(1)=F1/B1
      F(2)=A1/B1
      F(3)=F2/B2
      F(4)=A2/B2
      RR=0,0
      SS=0,0
      PP=0,0
      QQ=0,0
      DO 600 I=1,MM
      RR=RR+R(I)
      SS=SS+S(I)
      PP=PP+P(I)
      QQ=QQ+Q(I)
  600 CONTINUE
C
C*********     C = 4X2 MATRIX  =FIRST COLUMN IS AVERAGE ENERGY FOR EACH
C                              OF THE FOUR COLLISION REGIONS F1,A1,F2,A2
C                              =SECOND COLUMN IS MAXIMUM COLLISION ENERGY
C                              IN F1,A1,F2,A2
```

```
      C             C1 = MAXIMUM COLLISION ENERGY IN B1
      C             C2 = MAXIMUM COLLISION ENERGY IN B2
      C*********    CC = MAXIMUM COLLISION ENERGY OUT OF ALL 4N POINTS (N=MM=XM)
      C
            C(1,1)=RR/XM
            C(2,1)=SS/XM
            C(3,1)=PP/XM
            C(4,1)=GG/XM
            C(1,2)=AMAX1(R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10))
            C(2,2)=AMAX1(S(1),S(2),S(3),S(4),S(5),S(6),S(7),S(8),S(9),S(10))
            C(3,2)=AMAX1(P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9),P(10))
            C(4,2)=AMAX1(G(1),G(2),Q(3),G(4),G(5),Q(6),Q(7),G(8),G(9),G(10))
            C1=AMAX1(C(1,2),C(2,2))
            C2=AMAX1(C(3,2),C(4,2))
            CC=AMAX1(C1,C2)
      C
      C*********    F1,A1,F2,A2 IS USED TO FIND "D'S" - STORE IN T VECTOR
      C
        750 MM=A(35)
            V1=A(23)
            V2=A(22)
            IF (MM .GT. 1) GO TO 800
      C                 PARALLEL MEETING
            V=V1+V2
            T(1)=F1*(V1/V)
            T(2)=A1*(V1/V)
            T(3)=F2*(V2/V)
            T(4)=A2*(V2/V)
            GO TO 1000
        800 IF (V2 .GT. V1) GO TO 900
      C                 PARALLEL OVERTAKING, V2>V1
            T(1)=F1
            T(2)=A1
            T(3)=F2*(V2/V1)
            T(4)=A2*(V2/V1)
            GO TO 1000
      C                 PARALLEL OVERTAKING, V1>V2
        900 T(1)=F1*(V1/V2)
            T(2)=A1*(V1/V2)
            T(3)=F2
            T(4)=A2
       1000 DO 1275 L=1,4,3
            IF (L .EQ. 4) GO TO 1300
      C
      C*********    U MATRIX IS 9X4 WHERE 9 ROWS CORRESPOND TO THE 9 TYPES OF
      C             OUTPUT DESCRIBED EARLIER IN PROGRAM INPUT.
      C                FIRST COLUMN - CONTAINS DISTANCE "D"
      C                         WEIGHTED SO THAT ALL 9 VIEWPOINTS MAY
      C                         BE COMPARED.  THAT IS, IF U(6,1) IS GREATER THAN
      C                         U(1,1) THEN THERE IS BETTER THAN A 1 IN 4 CHANCE
      C                         OF THIS COLLISION OCCURING GIVEN A COLLISION WILL TAKE
      C                         PLACE, OR, GIVEN THE FOUR TYPES OF COLLISIONS THIS
      C                         ONE IS DISPROPORTIONATELY MORE LIKELY.
      C             SECOND COLUMN- WEIGHTED AVERAGE OF COLLISION ENERGY, OR
      C                         SIMPLY THE EXPECTED ENERGY OF COLLISION,,
      C                         IF F1=A1=F2=A2 THEN EXPECTED ENERGY WOULD BE JUST
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              C                      1/4 OF C(1,1)+C(2,1)+C(3,1)+C(4,1).
              C
              C
              C               THIRD COLUMN - THE MAXIMUN COLLISION ENERGY OUT OF ALL
              C                      THE 40 CALCULATED ENERGIES, FOR U(1,3), OR OUT OF
              C                      WHICHEVER SET OF POINTS IS APPROPRIATE FOR THE
              C                      SELECTED ROW OF U.
              C               FOURTH COLUMN - THE FIRST COLUMN TIMES PROBABILITY OF RUPTURE
              C                      GIVEN COLLISION.
              C
0063           1030 U(1,L)=(T(1)+T(2)+T(3)+T(4))/2.
0064                U(2,L)=T(2)+T(3)
0065                U(3,L)=T(1)+T(4)
0066                U(4,L)=T(1)+T(2)
0067                U(5,L)=T(3)+T(4)
0068                U(6,L)=T(1)*2.
0069                U(7,L)=T(2)*2.
0070                U(8,L)=T(3)*2.
0071                U(9,L)=T(4)*2.
0072           1050 IF (L .EQ. 4) GO TO  1850
0073           1100 U(1,2)=(F1*C(1,1)+A1*C(2,1)+F2*C(3,1)+A2*C(4,1))/(B1+B2)
0074                U(2,2)=(A1*C(2,1)+F2*C(3,1))/(A1+F2)
0075                U(3,2)=(F1*C(1,1)+A2*C(4,1))/(F1+A2)
0076                U(4,2)=F(1)*C(1,1)+F(2)*C(2,1)
0077                U(5,2)=F(3)*C(3,1)+F(4)*C(4,1)
0078                U(6,2)=C(1,1)
0079                U(7,2)=C(2,1)
0080                U(8,2)=C(3,1)
0081                U(9,2)=C(4,1)
0082                U(1,3)=CC
0083                U(2,3)=AMAX1(C(2,2),C(3,2))
0084                U(3,3)=AMAX1(C(1,2),C(4,2))
0085                U(4,3)=C1
0086                U(5,3)=C2
0087                U(6,3)=C(1,2)
0088                U(7,3)=C(2,2)
0089                U(8,3)=C(3,2)
0090                U(9,3)=C(4,2)
0091           1275 CONTINUE
              C
              C*********      J1 - TOTAL NO. OF COMBINATIONS OF SYSTEM PARAMETER VALUES GO
              C               BACK TO PROGRAM INPUT AND SET UP A NEW SET OF INPUT VALUES IN
              C*********      "MATRIX", IF J LESS THAN J1.
0092                IF J=J1 STOP
0093                J=J+1
0094                RETURN
              C************************** HULL RUPTURE SUBMODEL ***************************
              C*********      THIS LAST SECTION OF PROGRAM OUTPUT IS FOR SENSITIVITY ON
              C               RUPTURE PROBABILITY WHEN A VALUE OF ENERGY TO RUPTURE HULL
              C                     E1 - ENERGY TO RUPTURE HULL OF SHIP 1, IN FT-LBS
              C                     E2 - ENERGY TO RUPTURE HULL OF SHIP 2, IN FT-LBS
              C               R1 IS THE FRACTION OF THE TEN POINTS IN F1 WHERE COLLISION
              C*********      RESULTED IN ENERGY W, IN P(I), GREATER THAN E2.
              C*********      THE SAME APPLIES FOR OTHER 3 CASES - A1,F2,A2.
0095           1300 E1=A(6)
0096                E2=A(5)
```

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0097           R1=0.0
0098           S1=0.0
0099           P1=0.0
0100           G1=0.0
0101           DO 1700 I=1,MM
0102           IF (R(I) .LT. E2) GO TO 1400
0103           R1=R1+(1./XM)
0104      1400 IF (S(I) .LT. E1) GO TO 1500
0105           S1=S1+(1./XM)
0106      1500 IF (P(I) .LT. E1) GO TO 1600
0107           P1=P1+(1./XM)
0108      1600 IF (G(I) .LT. E2) GO TO 1700
0109           G1=G1+(1./XM)
0110      1700 CONTINUE
         C
0111      1800 T(1)=R1*T(1)
0112           T(2)=S1*T(2)
0113           T(3)=P1*T(3)
0114           T(4)=G1*T(4)
0115           GO TO 1030
0116      1850 CONTINUE
         C
0117           WRITE(6,1860)
0118      1860 FORMAT(1X/// 5X,'U MATRIX - FOR USE IN PREPARATION OF BASELINE ',
              C'CASE DATA DECK'/)
0119           DO 1870 I=1,9
0120           TEMP1=U(I,1)
0121           TEMP2=U(I,2)
0122           TEMP3=U(I,3)
0123           TEMP4=U(I,4)
         C                   WRITE OUT "U" MATRIX
0124           WRITE (6,1890) I,TEMP1,TEMP2,TEMP3,TEMP4
0125      1890 FORMAT (1X,I2,4(F15.1))
0126      1870 CONTINUE
         C
         C*********      WRITE OUT OUTPUT WITH DIVISION BY BASE CASE.  IF "TEMP1" IS 20%
         C               FOR EXAMPLE, THEN THIS PARTICULAR SET OF INPUTS IS EXPECTED TO
         C               YIELD 20% MORE COLLISION THAN IN THE BASE CASE.  FOR TEMP1=-20%
         C               20% FEWER COLLISIONS ARE EXPECTED.
         C               THIS COMPUTATION IS ESSENTIALLY A MATRIX DIVISION, SUBTRACTION
         C               OF 1.0, AND MULTIPLYING BY 100%, I.E.
         C*********             (U(CURRENT)/U(BASE CASE)-1.0)X100%
         C
         C                   WRITE OUT PERCENTAGE CHANGE (SENSITIVITY ANALYSIS3) MATRIX
0127           WRITE (6,1885)
0128      1885 FORMAT (1X,///////,30X,'PERCENTAGE  CHANGES',///)
0129           WRITE (6,1887)
0130      1887 FORMAT(1X,'ERRING',2X,'STRUCK', 7X,'PROB OF',6X,'AVG COLL',
              C6X,'MAX COLL', 7X,'PROB OF',/,1X,'VESSEL',2X,'VESSEL',6X,
              C 'COLLISION',6X,'ENERGY',8X,'ENERGY', 8X,'RUPTURE',/)
0131           DO 1880 I=1,9
0132           TEMP1=((U(I,1)/BASE1(I,1))-1.)*100.
0133           TEMP2=((U(I,2)/BASE1(I,2))-1.)*100.
0134           TEMP3=((U(I,3)/BASE1(I,3))-1.)*100.
0135           TEMP4=((U(I,4)/BASE1(I,4))-1.)*100.
0136           WRITE(6,1888) ERR(I),HIT(I),TEMP1,TEMP2,TEMP3,TEMP4
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0137          1889 FORMAT(1X,2A8,F10.1,'%',3(F13.1,'%'))
0138          1880 CONTINUE
            C*********    RETURN TO INPUT IF J<J1, LIKE BEFORE.
0139               IF J=J1 STOP
0140               J=J+1
0141               RETURN
0142               END
```


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318X